nature portfolio

# Peer Review File

# Wireless microwave-to-optical conversion via programmable metasurface without DC supply

Corresponding Author: Professor Wei Xiang Jiang

**This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.**

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors present a bidirectional microwave-optical link capable of interfacing an air-water boundary. The microwave-optical is designed around a double-sided metasurface. On one side, Schottky diodes are used to capture microwave signals, which are then converted to DC to drive a laser diode. On the opposite side, pn-junction diodes function as tunable capacitances, controlled by incident light, allowing the metasurface's resonant behavior to be switched. The bidirectional link operates with two microwave signals of orthogonal polarizations.

The concept is intriguing and holds significant potential for applications in remote and harsh environments, offering a bridge between microwave and optical links (either free-space or fiber) with minimal energy consumption. However, the manuscript requires substantial improvement in writing before it can be considered for publication. The text is often unnecessarily complex, making it difficult to follow. Specifically, the bidirectional concept and the underlying physics of the conversion process need to be explained more clearly. Below are additional comments that the authors should address:

- Microwave Back Channel Sourcing: How is the microwave back channel sourced? It appears to be based on detecting changes in the reflection of a continuous-wave (CW) microwave signal.
o This approach would require a constant microwave signal to validate the back channel. The authors should clarify this and provide more information on the power and efficiency costs involved.
o For a true bidirectional link, a separate microwave reading signal would be needed for the optical-to-microwave conversion. In that case, how does cross-talk impact the link when modulation is introduced into the transmitted microwave signal?
- Ultrafast Link Claim: The claim of an ultrafast link is unconvincing.
o What are the factors limiting the speed of the link?
o What potential improvements could increase the speed, and how feasible is it to extend the system to higher microwave frequencies for greater channel bandwidth?
o What applications do the authors envision for such a low-speed link?
- Power Requirements for the Laser Diode: The power required to drive the laser diode seems quite high. Is the specified power (e.g., 100W) measured at the source or at the metasurface? If it's the latter, free-space losses will further increase the required power, posing significant challenges.
o The experiment appears to place the antenna directly in front of the metasurface. Have the authors considered increasing the distance, and if so, how does it affect the power requirements?
- Optical-to-Microwave Link and pn-Junction Elements: The optical-to-microwave link relies on multiple pn-junction elements. How is the laser beam (presumably small at the start) mapped onto the metasurface?
o Is any beam shaping involved to cover a larger area?
o If the optical beam is small and non-uniformly illuminates the metasurface (affecting only a portion of the pn-junctions), how does this impact the reflection? Additionally, would water turbulence affect the link?

Reviewer #2

(Remarks to the Author)
The authors present a neat idea of a device that will be converting microwave signals to optical as well as encode optical signals onto microwaves. My main two concerns that I want authors to address are

1) Make claims more clear. For example, they say that the device does not need power to operate to do conversions. While this is technically true, there is no active elements in the metasurface, the microwave read-out needs an incident microwave signal that carries power. For larger distances, the required power can become too large. This brings me to the question 2:
2) The practicality of this approach is questionable. I think that in the main body of the manuscript they should specify the main performance characteristics. This includes what is the conversion efficiency of the microwave power into optical power - e.g. if I send 1W per square centimeter at microwave frequency, what will be the light output? In figure 1 they have the drawing of the sattelite communication utilising this device. How much microwave power will satellite need to send to Earth in order to then receive the modulated microwave signal? What is the output energy in the laser beam is needed to modulate the microwaves if the object is 100m (or any other distance) underwater?

Technical comments:

Zero-power and battery-free in the same sentence is not needed. "enough intensity" - please define.

Multiple grammatic errors

"Very fast" is relative, and "hundreds of kHz" is not that fast in some applications.

For simulations, authors use "when the Schottky diode operates in the on state". The "on" state for a diode means that it is positively biased, which means that there should be a source of voltage applied to it. However authors do not have this - please write this section more clearly.

Phrases like "When spatial laser is incident on the meta-element" are a bit ambiguous. What laser is called spatial? What does it mean the laser is incident (sounds like the laser is thrown onto meta-element)

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have addressed convincingly all my comments.

Reviewer #2

(Remarks to the Author)
I thank the authors for responding to my comments. They answered all my questions well. Probably The eq 5 in response is upside-down? Otherwise the efficiency would always be greater than 1.

I am still a bit confused how the Shottky diode becomes positively biased under the RF signal. The diode conducts during the positive cycle of RF signal, and does not conduct during negative part of the cycle of RF signal. This creates negative voltage on the diode. So the bias should be negative, i.e. the diode in off state?

I still think that the English needs improvement for readability, and hope that the editorial office can help with this.

# Responses to Reviewers' Comments

We thank both reviewers very much for their good comments and useful suggestions, which make the manuscript more accurate and clearer. We have read the reviewers' comments carefully and addressed all comments point-by-point by providing more detailed analyses, results, and discussions. We revised the manuscript thoroughly based on these comments and suggestions. The revised part is highlighted in **blue fonts** in the revised manuscript. Below are our detailed responses.

## To Reviewer #1

**General Comment:** The authors present a bidirectional microwave-optical link capable of interfacing an air-water boundary. The microwave-optical is designed around a double-sided metasurface. On one side, Schottky diodes are used to capture microwave signals, which are then converted to DC to drive a laser diode. On the opposite side, pn-junction diodes function as tunable capacitances, controlled by incident light, allowing the metasurface's resonant behavior to be switched. The bidirectional link operates with two microwave signals of orthogonal polarizations. The concept is intriguing and holds significant potential for applications in remote and harsh environments, offering a bridge between microwave and optical links (either free-space or fiber) with minimal energy consumption. However, the manuscript requires substantial improvement in writing before it can be considered for publication. The text is often unnecessarily complex, making it difficult to follow. Specifically, the bidirectional concept and the underlying physics of the conversion process need to be explained more clearly.

**Our Reply:**

Thank you very much for your very positive comments and useful suggestions. These insightful comments are very constructive to improve the work. We have addressed all points and revised the manuscript accordingly.

**Comment 1:** Microwave Back Channel Sourcing: How is the microwave back channel sourced? It appears to be based on detecting changes in the reflection of a continuous-wave (CW) microwave signal.

**Our Reply:**

Thank you for your good question on the microwave back-channel sourcing. In our demonstration, we adopt directly the air-fed module that contains a microwave source and a connected high-directional horn antenna to provide required incident microwave, as shown in **Fig. R1**. The source emits the microwave signal, which is then transmitted through the horn antenna to illuminate the metasurface. That is to say, the microwave back channel is sourced by the air-fed module. In this case, the optical-to-microwave conversion is achieved by using laser to modulate the reflection features of incident microwave. The active air-fed scheme is very effective and is often used in metasurface implementation because it can provide stable microwave incidence, including the required polarization, frequency and power. Besides the common air-fed approach, some new metasurfaces have also been investigated recently to receive passively EM waves from environment, such as Wi-Fi signals[R1] and remote base- station signals[R2]. These attempts provide more possibilities for the feeding methods of metasurfaces, and are helpful to further reduce the power consumption of the overall system.

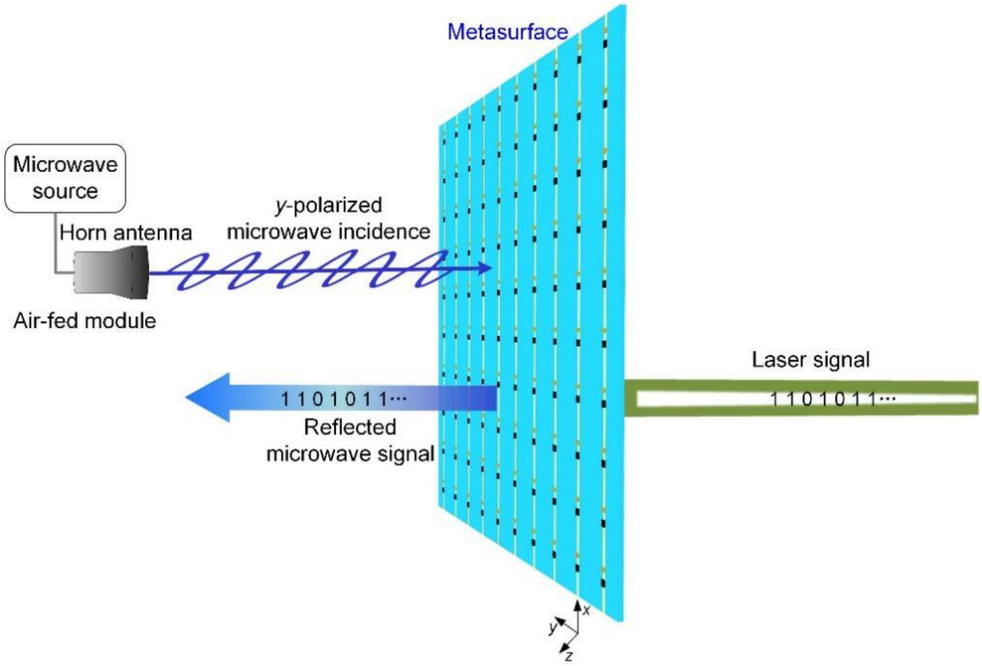


**Fig. R1. Schematic of the metasurface-based optical-to-microwave conversion.** An air-fed module consisting of a microwave source and a connected high-directional horn antenna is adopted to provide required incident microwave.

[R1] Zhao, H., Shuang, Y., Wei, M., Cui, T. J., Hougne, P. D. & Li, L. Metasurface-assisted massive backscatter wireless communication with commodity Wi-Fi signals. *Nat. Commun.* **11**, 3926 (2020).

[R2] Sang, J. et al. Coverage enhancement by deploying RIS in 5G commercial mobile networks: field trials. *IEEE Wireless Commun.* **31**, 172-180 (2024).

**According to your suggestions, the corresponding revisions are as below:**

We have added **Fig. R1** in the Supplementary Information (**Supplementary Fig. 1**), and provided some details and discussions on the microwave back-channel sourcing method (See the first paragraph of **Supplementary Note 1**).

"**Supplementary Note 1. Microwave incidence method**

The optical-to-microwave conversion is achieved by using laser to modulate the reflection characteristics of incident microwave. In our demonstration, we directly adopt the air-fed module that contains a microwave source and a connected high-directional horn antenna to provide required incident microwave, as shown in **Supplementary Fig. 1**. The source emits the microwave signal, which is then transmitted through the horn antenna to illuminate the metasurface. The active air-fed scheme is very effective and is often used in the metasurface implementation because it can provide stable microwave incidence, including required polarization, frequency and power. Besides the common air-fed approach, some metasurfaces have also been investigated recently to receive passively EM waves from environment, such as Wi-Fi signals[1] and remote base-station signals[2]. These attempts provide more possibilities for feeding methods of metasurfaces, and are helpful to reduce the power consumption of the overall system."

**Comment 2:** This approach would require a constant microwave signal to validate the back channel. The authors should clarify this and provide more information on the power and efficiency costs involved.

**Our Reply:**

Thank you very much for your helpful suggestion on the power and efficiency of the air-fed method. Unlike the microwave-to-optical conversion that requires strong microwave power to drive the laser diode, the power of the air-fed module is low. In the optical-to-microwave conversion channel, we detect power changes in reflected microwave signals, thus a significant difference in the reflected energy is required, rather than a high incident power. In experiments, the power of the microwave source is 1 mW. For the air-fed module, the received microwave power $P_r$ by the metasurface can be calculated by the Friis transmission equation[R3]:

$$P_r = \frac{G_t A_m}{4\pi d^2} P_t \quad (1)$$

where $P_t$ is transmitted power, $G_t$ is the gain of the horn antenna, $A_m$ is the effective aperture of the metasurface, and $d$ is the distance between the horn antenna and the metasurface. Therefore, the transmission efficiency $\eta$ can be calculated by:

$$\eta = \frac{P_r}{P_t} = \frac{G_t A_m}{4\pi d^2} \tag{2}$$

in addition, to generate quasi-plane wave incidence, the distance $d$ needs to satisfy far-field condition:

$$d > \frac{2D^2}{\lambda} \tag{3}$$

where $D$ is the aperture of the antenna, and $\lambda$ is the wavelength in free space. According to **Eq. (2)**, for the fabricated metasurface and the selected horn antenna, the transmission efficiency $\eta$ depends on the distance $d$. In experiments, we adopted a horn antenna with gain $G_t$ of 11 dBi at 4.45 GHz, and the fabricated metasurface covers an effective area of 300 x 150 $mm^2$. The horn antenna was fixed 0.25 m away from the metasurface sample, and thus, the far-field transmission efficiency $\eta$ is calculated as 74.5%.

[R3] Friis, H. T. A note on a simple transmission formula. *Proc. IRE* **34**, 254-256 (1946).

**According to your suggestions, the corresponding revisions are as below:**

1) In the first paragraph of **Page 9** in the revised manuscript, the power of the used air-fed module has been provided.

"Unlike the microwave-to-laser conversion that needs strong microwave power to drive the laser diode, we note that the required microwave power for the optical-to-microwave conversion is low. In the experiment, the power of the microwave source is 1 mW. Because we detect the power changes in the reflected microwave signals, a significant difference in the reflected energy is required, rather than a high incident power."

2) We have added the information on efficiency calculation method of the air-fed module in the Supplementary Information (See the second paragraph of **Supplementary Note 1**).

"For the air-fed module, the received microwave power $P_r$ by the metasurface can be calculated by the Friis transmission equation[3]:

$$P_r = \frac{G_t A_m}{4\pi d^2} P_t \quad \text{(S1)}$$

where $P_t$ is transmitted power, $G_t$ is the gain of the horn antenna, $A_m$ is the effective aperture of the metasurface, and $d$ is the distance between the horn antenna and the metasurface. Therefore, the transmission efficiency $\eta$ can be calculated by:

$$\eta = \frac{P_r}{P_t} = \frac{G_t A_m}{4\pi d^2} \quad \text{(S2)}$$

in addition, to generate quasi-plane wave incidence, the distance $d$ needs to satisfy far-field condition:

$$d > \frac{2D^2}{\lambda} \quad \text{(S3)}$$

where $D$ is the aperture of the antenna, and $\lambda$ is the wavelength in free space. According to **Eq. (S2)**, for the fabricated metasurface and the selected horn antenna, the transmission efficiency $\eta$ depends on the distance $d$. As the distance increases, the transmission efficiency decreases."

3) In the "**Details on system prototype**" Section in the revised manuscript, the efficiency of the used air-fed module has been provided.

"The gain of the used *y*-polarized horn antenna is 11 dBi at 4.45 GHz, and it was fixed 0.25 m away from the metasurface sample. By using **Eq. (S2)**, the far-field transmission efficiency is calculated as 74.5%."

**Comment 3:** For a true bidirectional link, a separate microwave reading signal would be needed for the optical-to-microwave conversion. In that case, how does cross-talk impact the link when modulation is introduced into the transmitted microwave signal?

**Our Reply:**

Thank you very much for your good question. For the microwave-to-optical conversion channel, a microwave source is essential. As you mentioned, the optical-to-microwave conversion channel also requires a separate microwave excitation source. Thus, for a true bidirectional link, how to avoid microwave signal crosstalk between such two channels must be considered. To minimize unexpected crosstalk, we have used simultaneously two isolation techniques on the metasurface. Firstly, we employ the polarization isolation, that is, two incoming microwaves for the bidirectional links are orthogonally polarized. When the orthogonal *x*- and *y*-polarized microwaves propagate into the metasurface, changing the state of the diode (modulation is introduced) in the cross-polarization direction has no effect on the reflection amplitude, as shown in **Fig. R2**. Secondly, we employ the frequency isolation, that is, the metasurface is operated at two different microwave frequencies for bidirectional conversions. Therefore, based on the polarization-frequency joint isolation scheme, the impact of crosstalk on bidirectional links can be ignored, and thus the metasurface can realize simultaneous and independent transmissions of dual-channel videos, as presented in **Supplementary Movie 1**.

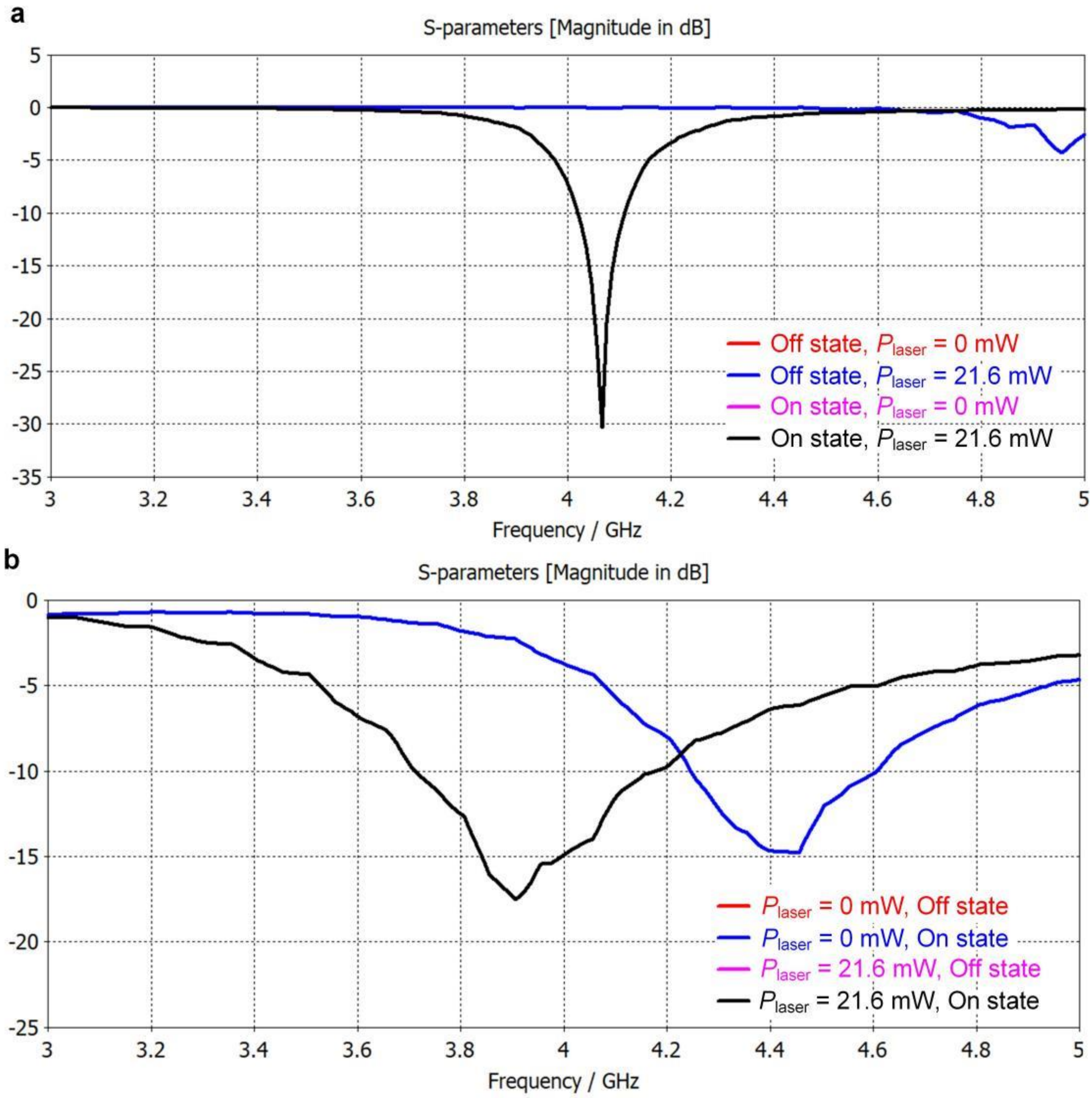


**Fig. R2. Simulated reflection amplitudes of the meta-element with different configurations under *x*- and *y*-polarized incidences to evaluate cross polarization isolation. a**, For *x*-polarized microwave incidence, changing the state of the photodiode in the cross-polarization direction has no effect on the resonance response. **b**, For *y*-polarized microwave incidence, changing the state of the Schottky diode in the cross-polarization direction has no effect on the resonance response.

**According to your suggestions, the corresponding revisions are as below:**

In the first and second paragraphs of **Page 7** in the revised manuscript, we have provided more discussion on how to avoid the unexpected cross-talk between the bidirectional links.

"In addition, to achieve low-crosstalk bidirectional conversion on one meta-element, we adopt a polarization-frequency joint isolation scheme. Specifically, the metal gaps in the resonant structures 1 and 2 are orthogonal, so that they respond to orthogonally-polarized microwaves, and the resonant frequencies of the two structures are different."

"We remark that when the *x*- or *y*-polarized wave propagates into the meta-element, changing the state of the diode in the cross-polarization direction has no effect on the resonance response, as shown in **Supplementary Fig. 6**. In addition, the meta-element is operated at different microwave resonant frequencies for bidirectional conversions. Therefore, based on the polarization-frequency joint isolation, the realized meta-element can work well in a full-duplex mode."

**Comment 4:** Ultrafast Link Claim: The claim of an ultrafast link is unconvincing.

**Our Reply:**

Thank you very much for your professional comment on the link speed. In current demonstrations based on the metasurface without any voltage source, data rates of 400 and 100 kbps over the microwave-to-laser and laser-to-microwave transmission links were achieved, respectively. You mentioned that the claim of an ultrafast link is unconvincing, and gave us several good suggestions (shown below). We addressed these questions carefully and provided more details and discussions on the link speed to present it clearer and more accurate in the revised manuscript.

**Comment 5:** What are the factors limiting the speed of the link?

**Our Reply:**

Thank you very much for your good question. We adopt the metasurface to implement the microwave and laser modulations for achieving the interconversion between microwave and laser signals. Therefore, the transmission rates of the bidirectional links mainly depend on the response speed of the designed metasurface and the used signal modulation mode. Because signal modulation is realized based on the state changing of the used Schottky diode and photodiode, thus their switching frequency is the main factor limiting the modulation speed of the metasurface. The switching frequency of a diode mainly depends on its junction capacitance value, involving the accumulation and recombination time of charge carriers[R4]. In addition, because all photodiodes in the metasurface are connected in parallel, resulting in a large capacitance, the number of photodiodes will also affect the speed. Therefore, in our design, a resistor is connected in parallel to photodiodes, providing a discharge circuit for generated photocarriers, which reduces the discharge time and thus increases the switching speed by 500 times.

[R4] Zhang, X. G. et al. A metasurface-based light-to-microwave transmitter for hybrid wireless communications. *Light: Sci. Appl.* **11**, 126 (2022).

**According to your suggestions, the corresponding revisions are as below:**

We have added some discussions on the main factors that affect the speed of the bidirectional link in the Supplementary Information (See the first paragraph of **Supplementary Note 7**).

"**Supplementary Note 7. Potential applications of links and their rate limiting factors**

Because signal modulation is realized based on the state changing of the used Schottky diode and photodiode, thus their switching frequency is the main factor that limits the modulation speed of the metasurface. The switching frequency of a diode mainly depends on its junction capacitance value, involving the accumulation and recombination time of charge carriers. In addition, because all photodiodes in the metasurface are connected in parallel, resulting in a large capacitance, the number of photodiodes will also affect the speed. Developing high-order modulation formats on metasurface can help improve link rates[6]. However, it will bring greater expenses, including power consumption and system complexity, due to requirement for precise modulation of more states on the metasurface."

**Comment 6:** What potential improvements could increase the speed, and how feasible is it to extend the system to higher microwave frequencies for greater channel bandwidth?

**Our Reply:**

Thank you very much for your helpful comments. As discussed above, the factors limiting the link rate are the switching speed of the loaded diodes and the used signal modulation mode. Therefore, the following three potential improvements could increase link rate. Firstly, in the current scheme, to achieve minimal energy consumption, there is no voltage source to connect to metasurface. External bias can be used to reduce the charge and discharge time of carriers, thereby increasing the switching speed of diodes. Secondly, in the future, we will have more opportunities to choose diodes with faster switching speed. Finally, developing high-order modulation schemes such as quadrature amplitude modulation (QAM)[R5] on the metasurface can help improve link rates. However, it will bring greater expenses, including power consumption and system complexity, due to requirement for precise modulation of more states on the metasurface.

It is feasible to extend the system to higher microwave frequencies based on our approach. Because the metasurface-enabled microwave-optical signal conversions are achieved based on diode modulations, the cut-off frequency of the used diodes determines mainly the microwave working frequencies of the system. To increase the microwave operating frequency of the metasurface, we could choose to use the Schottky diode[R6] and photodiode[R7] with high cut-off frequencies. Based on these high cut-off frequency diodes, we have down-scaled and optimized the meta-element to achieve higher microwave frequencies, as shown in **Fig. R3a**. The corresponding simulated results are shown in **Fig. R3b**. It is clear that the meta-element can produce an obvious absorption resonance at 12.68 GHz for *x*-polarized microwave incidence; for *y*-polarized microwave incidence, the reflection amplitude difference of 20 dB can be achieved at 14.28 GHz. Therefore, the metasurface can operate at higher microwave frequencies for greater bandwidth. In simulations, the off and on states of the Schottky diode are derived from its datasheet SPICE model[R8]; the tunable capacitance parameters of the photodiode are taken from Ref. [R7], and for the unilluminated and illuminated states, the capacitances of the photodiode are 12 and 35 fF, respectively.

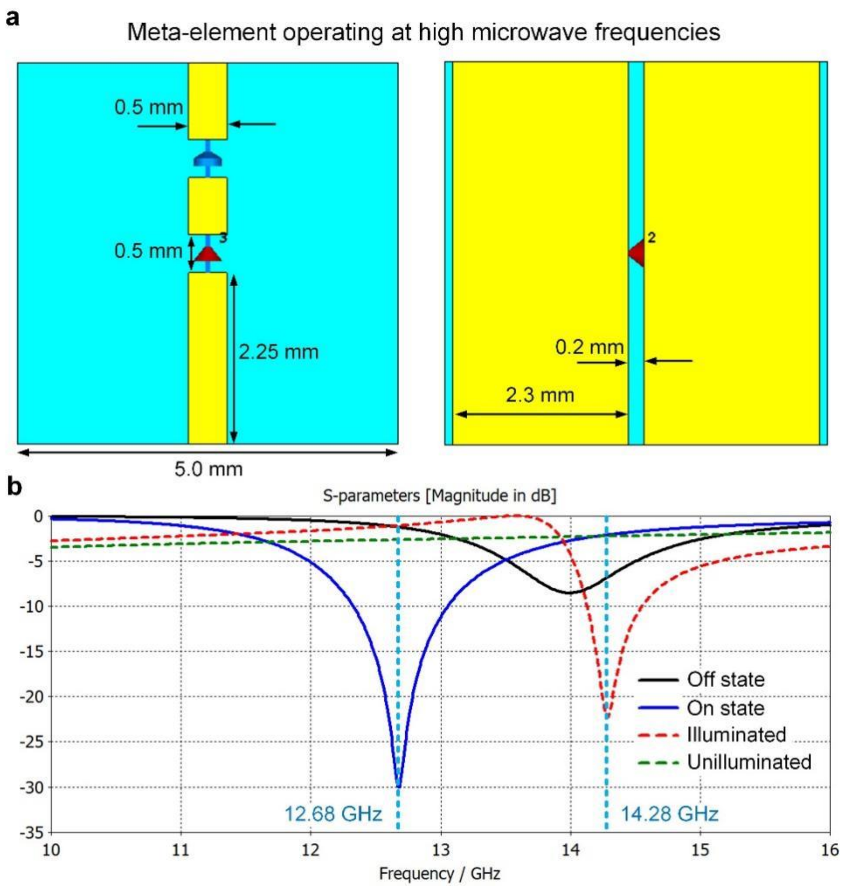


**Fig. R3. Optimized meta-element based on high cut-off frequency Schottky diode and photodiode for achieving higher microwave frequencies. a**, Simulation model of the high-frequency meta-element with a side length of 5.0 mm and a substrate thickness of 1.0 mm. **b**, Simulated microwave reflection amplitudes of the meta-element under different working states of Schottky diode and photodiode.

[R5] Chen, M. Z. et al. Accurate and broadband manipulations of harmonic amplitudes and phases to reach 256 QAM millimeter-wave wireless communications by time-domain digital coding metasurface. *Natl. Sci. Rev.* **19**, nwab134 (2022).

[R6] Wagih, M., Hilton, G. S., Weddell, A. S. & Beeby, S. Broadband millimeter-wave textile-based flexible rectenna for wearable energy harvesting. *IEEE Trans. Microw. Theory Techn.* **68**, 4960-4972 (2020).

[R7] Malyshev, S. A. & Chizh, A. L. P-I-N photodiodes for optical control of microwave circuits. *IEEE J. Sel. Topics Quantum Electron.* **10**, 679-685 (2004).

[R8] *Surface-Mount Schottky Diodes SMS7630 Series Datasheet* (SKYWORKS, 2021); https://www.skyworksinc.com/-/media/SkyWorks/Documents/Products/201-300/Surface_Mount_Schottky_Diodes_200041AG.pdf

**According to your suggestions, the corresponding revisions are as below:**

1) We have discussed the potential improvements that could increase the link speed in the "**Discussion**" Section in the revised manuscript.

"Transmission rates of the bidirectional links mainly depend on the switching speed of the loaded diodes and the used signal modulation mode (see **Supplementary Note 7** for more discussions). Therefore, the following potential improvements could be adopted in future to increase the link rate. Firstly, in the current scheme, to achieve minimal energy consumption, there is no voltage source to connect to metasurface. External bias can be used to reduce the charge and discharge time of carriers, thereby can increase the switching speed of diodes. Secondly, in the future, we will have more opportunities to choose diodes with faster switching speed. Finally, developing high-order modulation schemes such as quadrature amplitude modulation on the metasurface can help improve the link rates."

2) We have added **Fig. R3** in the Supplementary Information (**Supplementary Fig. 13**), and also provided some details on the design of the meta-element working at higher microwave frequencies (**Supplementary Note 8**).

"**Supplementary Note 8. Extending metasurface to higher microwave frequencies**

It is feasible to extend the system to higher microwave frequencies based on our approach. Because the metasurface-enabled microwave-optical signal conversions are achieved based on diode modulations, thus the cut-off frequency of the used diodes determines mainly the microwave working frequencies of the system. To increase the microwave operating frequency of the metasurface, we can choose to use the Schottky diode[7] and photodiode[8] with high cut-off frequencies. Based on these high cut-off frequency diodes, we have down-scaled and optimized the meta-element to achieve higher microwave frequencies, as shown in **Supplementary Fig. 13a**. The corresponding simulated results are shown in **Supplementary Fig. 13b**. It is clear that the meta-element can produce an obvious absorption resonance at 12.68 GHz for *x*-polarized incident microwave; for *y*-polarized microwave, the reflection amplitude difference of 20 dB can be achieved at 14.28 GHz. Therefore, the metasurface can operate at higher microwave frequencies for greater bandwidth. In simulations, the off and on states of the Schottky diode are derived from its datasheet SPICE model[9]; the tunable capacitance parameters of the photodiode are taken from **Supplementary Ref. 8**, and for the unilluminated and illuminated states, the capacitances of the photodiode are 12 and 35 fF, respectively."

**Comment 7:** What applications do the authors envision for such a low-speed link?

**Our Reply:**

Thank you very much for your helpful suggestion. We have realized 400 and 100 kbps data rates over the microwave-to-laser and laser-to-microwave transmission links, respectively, based on the metasurface that does not require any external voltage source. As you highly commented, our approach offers a bridge between microwave and optical links with minimal energy consumption, holding significant potential for applications in remote and harsh environments. Especially in marine environment, battery free is highly desired. In fact, 400 and 100kbps communication links are good to transmit high-quality text, images, audio, and we also verified that they can be used for general-quality video transmission. Therefore, the microwave-optical bidirectional conversion links have potentials in air-water cross-media wireless communication. For example, underwater detection equipment (e.g., an unmanned undersea vehicle) can wirelessly transmit collected ocean data (e.g., underwater images) to a drone in real time. At the same time, the drone can also send real-time control commands to an underwater equipment to instruct it to implement specific tasks (e.g., underwater cruising). This is crucial for marine environment monitoring, underwater resource exploitation, and marine scientific research, as it helps to achieve true unmanned and full-time operations.

**According to your suggestions, the corresponding revisions are as below:**

We have added some discussions on the potential applications of the bidirectional links in the Supplementary Information (See the second paragraph of **Supplementary Note 7**).

"In fact, 400 and 100kbps communication links are sufficient to transmit high-quality text, images, and audio. We also verified that they can be used for general-quality video transmission. Therefore, the microwave-optical bidirectional conversion links have potentials in air-water cross-media wireless communication. For example, underwater detection equipment (e.g., an unmanned undersea vehicle) can wirelessly transmit collected ocean data (e.g., underwater images) to a drone in real time. At the same time, the drone can also send real-time control commands to an underwater equipment to instruct it to implement specific tasks (e.g., underwater cruising). This is crucial for marine environment monitoring, underwater resource exploitation, and marine scientific research, as it helps to achieve true unmanned and full-time operations.”

**Comment 8:** Power Requirements for the Laser Diode: The power required to drive the laser diode seems quite high. Is the specified power (e.g., 100W) measured at the source or at the metasurface? If it’s the latter, free-space losses will further increase the required power, posing significant challenges.

**Our Reply:**

Thank you very much for your kind reminder and good question. The third aspect that you concerned about is the power requirements for the laser diode. We have provided a schematic of the power transmission process of the microwave-to-optical conversion, as shown in **Fig. R4**. The $P_s$ is the power of microwave source and $G_a$ is the gain of the power amplifier. Because the source power $P_s$ and the amplifier gain $G_a$ are known, the "input microwave power" mentioned in our original manuscript refers to the provided total power $P_{total} = P_s + G_a$, not the received microwave power $P_r$ of the metasurface. Obviously, the total power $P_{total}$ is the ideal power of the system, which not only includes the available power, but also includes the power losses caused by coaxial cables, connectors, and free space. Therefore, the total microwave power may seem a bit high. However, the required transmitted power $P_t = P_{total} - 2P_{loss}$ is less than the ideal total power $P_{total}$. We have tested the power loss $P_{loss}$ of one used coaxial cable and connector, and it is 3 dB. The experimental results in **Fig. 2d** in the original manuscript show that when the total power $P_{total}$ reaches 100mW (20 dBm), the laser diode has been lit and the output power $P_o$ is 2.7 mW. In fact, the available transmitted power $P_t$ at this time is only 25 mW (14 dBm).

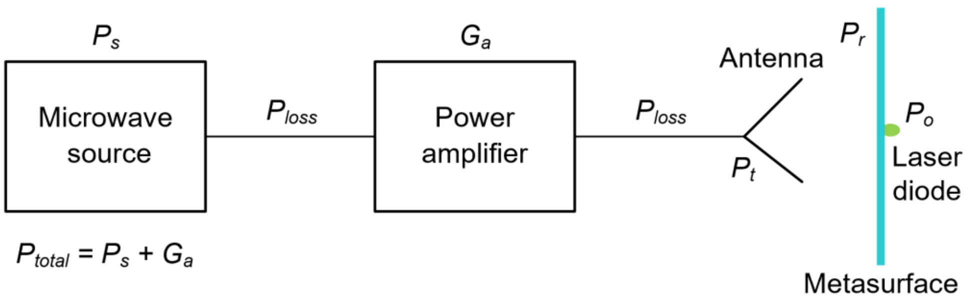


**Fig. R4. Schematic of power transmission process of the microwave-to-optical conversion.** The input microwave power refers to the microwave power $P_t$ fed into the transmitting horn antenna.

**According to your suggestions, the corresponding revisions are as below:**

In the revised manuscript, to make the description of power requirements more accurate, we have clearly defined the "incident microwave power", which refers to the microwave power fed into the transmitting horn antenna, and we have modified **Fig. 2d** correspondingly. Under this definition, free-space loss has also been taken into account.

"Here, the input microwave power refers to the microwave power fed into the transmitting horn antenna."

**Comment 9:** The experiment appears to place the antenna directly in front of the metasurface. Have the authors considered increasing the distance, and if so, how does it affect the power requirements?

**Our Reply:**

Thank you very much for your professional suggestion. There is a strong relationship between the required microwave power and antenna distance *d*, as free-space loss has a significant impact on microwave transmission efficiency. As discussed in "**Comment 2**", when the distance *d* is very large, the microwave transmission efficiency is low because a considerable amount of microwave energy is lost in free space. To improve transmission efficiency and reduce the input microwave power, we consider placing the horn antenna in the near-field region. In this case, the microwave transmission efficiency can be calculated using the following formula[R9]:

$$\eta = \frac{P_r}{P_t} = 1 - e^{-\tau^2} \tag{4}$$

where $\tau^2 = G_t A_m / 4\pi d^2$, which is closely related to distance *d*. The $P_t$ and $P_r$ are the transmitted microwave power from the antenna and the received microwave power of the metasurface, respectively. In the microwave-to-optical conversion experiment, the gain $G_t$ of used horn antenna is 15 dBi and the metasurface area $A_m$ is 300 x 150 $mm^2$. In this case, the calculated transmission efficiencies $\eta$ at near field with different distances *d* are plotted in **Fig. R5**. It is clear that in the near-field region, when the antenna distance *d* is small, the transmission efficiency can approach 100%, that is, the microwave energy radiated by the horn antenna is almost completely received by the metasurface. In our experiment, the distance *d* is 0.1 m, and thus the transmission efficiency $\eta$ is 99.9%. If we increase the antenna distance, the transmission efficiency will decrease and thus the transmitted power needs to be increased. As a demonstration, we added a communication experiment in which the distance *d* was increased to about 0.3 m, and then we increased the transmission power by 2dB. It is clear that the communication system can still work well, as presented in case 2 in **Supplementary Movie 1**.

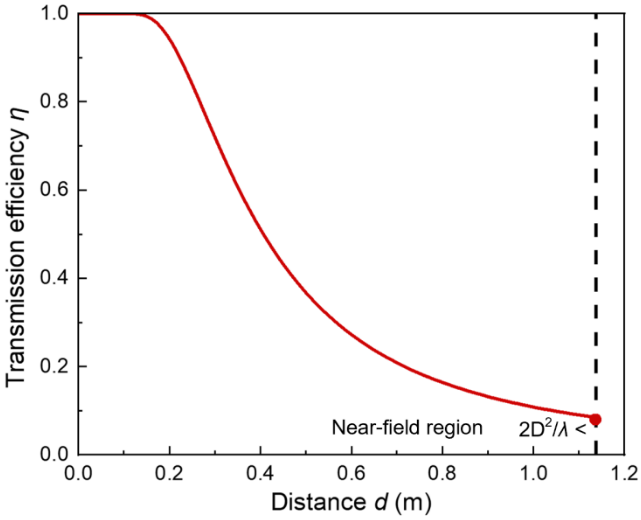


**Fig. R5. Calculated microwave transmission efficiency *η* at near field with different antenna distances *d*.** When the antenna distance *d* is small, the transmission efficiency can reach nearly 100%.


[R9] Brown, W. C. Adapting microwave techniques to help solve future energy problems. *IEEE Trans. Microw. Theory Techn.* **21**, 753-763 (1973).


**According to your suggestions, the corresponding revisions are as below:**

We have added **Fig. R5** in the Supplementary Information (**Supplementary Fig. 9**), and also provided some discussions on the impact of distance on power requirements (**Supplementary Note 4**). We have added a transmission experiment when increasing the antenna distance (See case 2 in **Supplementary Movie 1**).

**"Supplementary Note 4. Near-field transmission efficiency**

There is a strong relationship between the required microwave power and the antenna distance *d*, as free-space loss has a significant impact on microwave transmission efficiency. To improve transmission efficiency and reduce the input microwave power, for microwave-to-laser conversion, we consider placing the horn antenna in the near-field region. In this case, the microwave transmission efficiency can be calculated using the following formula[5]:

$$\eta = \frac{P_r}{P_t} = 1 - e^{-\tau^2} \quad \text{(S4)}$$

where $\tau^2 = G_t A_m / 4\pi d^2$, which is closely related to distance $d$. The $P_t$ and $P_r$ are the transmitted microwave power from the antenna and the received microwave power of the metasurface, respectively. In the microwave-to-optical conversion experiment, the gain $G_t$ of used horn antenna is 15 dBi and effective metasurface area $A_m$ is 300 × 150 $mm^2$. In this case, the calculated transmission efficiencies $\eta$ at near field with different distances $d$ are plotted in **Supplementary Fig. 9**. It is clear that in the near-field region, when the antenna distance $d$ is small, the transmission efficiency can reach nearly 100%.

In video transmission experiments, we first placed the horn antenna 0.1 m away from the metasurface sample (case 1), and the corresponding transmission efficiency $\eta$ is 99.9%. Then, as a demonstration, we increased the antenna distance to about 0.3 m (case 2), and at the same time, we increased the transmission power by 2 dB. For both two cases, the hybrid communication system can work well, as presented in **Supplementary Movie 1**."

**Comment 10:** Optical-to-Microwave Link and pn-Junction Elements: The optical-to-microwave link relies on multiple pn-junction elements. How is the laser beam (presumably small at the start) mapped onto the metasurface?

**Our Reply:**

Thank you very much for your kind reminder and good question. Your final concern is whether the metasurface requires a large light beam to illuminate all PN-junction elements (i.e., photodiodes) uniformly. The answer is no. We apologize for not explaining it clearly in our original manuscript. Although the metasurface contains multiple photodiodes, in fact, we just need to illuminate any one of them to drive the metasurface to work. This is achieved by our parallel design in meta-element array, as shown in **Fig. R6**. For optical-to-microwave meta-elements, along the *x* direction, the 20 resonant structures 2 in one row are connected naturally in parallel by their patches. Along the *y* direction, two patches in every row are connected to two designed metal lines at the both sides of the metasurface through stubs. Under this connection relationship, all the photodiodes are connected in parallel. In such a case, if one photodiode is illuminated and activated, the photogenerated potential difference will drive all other photodiodes to change their capacitances, and thus the required microwave reflection can be well realized. Therefore, only a small beam of focused laser is required to drive the metasurface to work, rather than a large spot to cover the entire metasurface, which greatly reduces the need for one-by-one alignment and the difficulty of light source design.

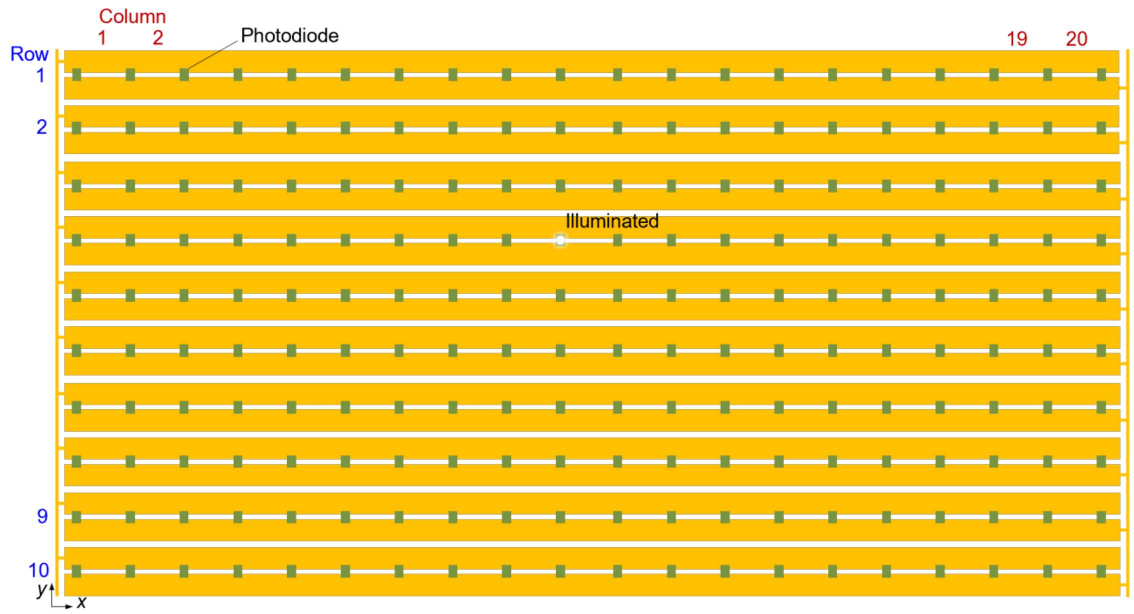


**Fig. R6. Schematic of the photodiode-based optical-to-microwave conversion structures and their connection relationship.** All the photodiodes are connected in parallel, and thus any one of them can be illuminated to drive the metasurface to work.

**According to your suggestions, the corresponding revisions are as below:**

In the first paragraph of **Page 8** in the revised manuscript, we have added more details on how to use one small beam of focused laser to drive the metasurface to work, and we have added **Fig. R6** in the Supplementary Information (**Supplementary Fig. 7**).

"In such a case, if one photodiode is illuminated and activated, the photogenerated potential difference will drive all other photodiodes to change their capacitances. Therefore, only a small laser beam is required to drive the metasurface to work, rather than a large spot to cover the entire metasurface, which reduces greatly the need for one-by-one alignment and the difficulty of light source design."

**Comment 11:** Is any beam shaping involved to cover a larger area?

**Our Reply:**

Thank you very much for your good question. As we discussed above, we don't need a complex light source to produce a large laser beam to illuminate the entire metasurface. In optical-to-microwave conversion experiment, we adopted a common laser unit to illuminate precisely and modulate the metasurface, and the diameter of the laser spot was only about 4 mm.

**According to your suggestions, the corresponding revisions are as below:**

We have added the spot size of the illuminated laser in the "**Experiments on microwave-laser conversion**" Section in the revised manuscript.

"The diameter of the laser spot was about 4.0 mm."

**Comment 12:** If the optical beam is small and non-uniformly illuminates the metasurface (affecting only a portion of the pn-junctions), how does this impact the reflection? Additionally, would water turbulence affect the link?

**Our Reply:**

Thank you very much for your good questions. Based on our element-parallel design discussed above, for optical-to-microwave conversion, the metasurface do not require a large light beam to illuminate all photodiodes uniformly. We can use a small laser beam to illuminate accurately a single photodiode for driving the metasurface. In previous experiments, we adopted one laser unit to generate a small laser beam with about 4 mm spot for controlling the microwave reflection of the metasurface, and 9 dB amplitude difference can be achieved at 4.45 GHz, as shown in **Fig. 2e** in the original manuscript. In fact, each photodiode can be illuminated independently to generate the desired microwave reflection. We have also measured the microwave reflection amplitudes of the metasurface when other photodiodes at different positions were illuminated, and the normalized results are shown in **Fig. R7**. It is clear that when photodiodes at other positions are illuminated, the metasurface can generate the same microwave reflection amplitude differences at 4.45 GHz. In addition to illuminating one photodiode, the metasurface can also work well when the both photodiodes are illuminated simultaneously. Therefore, we can use small laser beams to illuminate precisely and control metasurface, and multiple photodiodes also provide possibility for spatial diversity receiving.

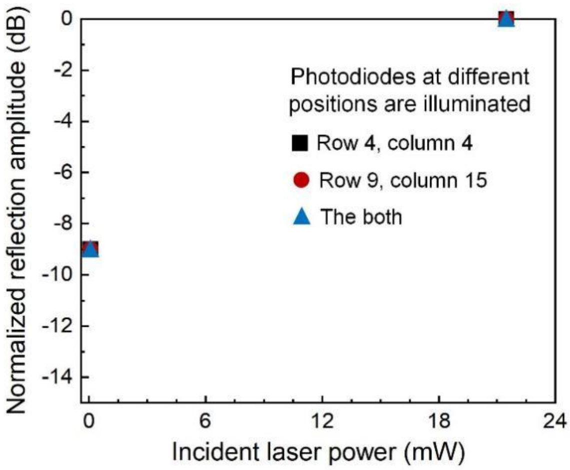


**Fig. R7. Measured normalized microwave reflection amplitudes of the metasurface at 4.45 GHz when photodiodes at different positions are illuminated.** It is clear that the metasurface can generate the same microwave reflection amplitude differences when photodiodes at other positions are illuminated.

Another issue you wondered is "would water turbulence affect the link?" We know that turbulence can cause random changes in the refractive index of water, leading to fluctuations of the transmitted light power, and thus affect the performance of underwater optical links. This is an open issue for underwater optical wireless communication[R10]. An effective way to mitigate the impact of turbulence on optical wireless transmission links is spatial diversity, such as utilizing multiple-input multiple-output (MIMO) technology[R11,R12]. Because MIMO can utilize multiple channels to carry the same transmission signal, it not only relaxes the optical link alignment conditions, but also avoids effectively the impact of turbulence on multiple signals simultaneously.

We have demonstrated that multiple laser beams can illuminate simultaneously multiple photodiodes to modulate microwave reflection of the metasurface. Therefore, on the metasurface platform, spatial diversity transmission can be developed and used to reduce turbulence-induced signal fluctuation. As a validation, we investigated experimentally the transmission performance of the metasurface-enabled laser-to-microwave wireless link when underwater turbulence is induced. The experimental setup is shown in **Fig. R8a**, in which the water tank, laser transmitter, and microwave receiver are the same as in the previous experiments. To generate obvious temperature-induced underwater turbulence, 20° tap water was first injected into the water tank, and then 60° hot water was injected into it from the top to down. In experiments, we tested the video transmission quality of the laser-to-microwave link when metasurface is illuminated by one laser signal and two identical laser signals simultaneously, and the transmission results are shown in **Fig. 8Rb,c,** respectively. For the case that one photodiode is illuminated, strong turbulence will cause the laser beam diffusion and drift in a short period of time, thereby reducing the transmission quality of the link. But when two photodiodes are illuminated simultaneously, the link can still provide relatively stable data transmission, because even though one laser beam is in outage, the another still ensure reliable operation, thus mitigating the impact of underwater turbulence. See **Supplementary Movie 2** for entire transmission process.

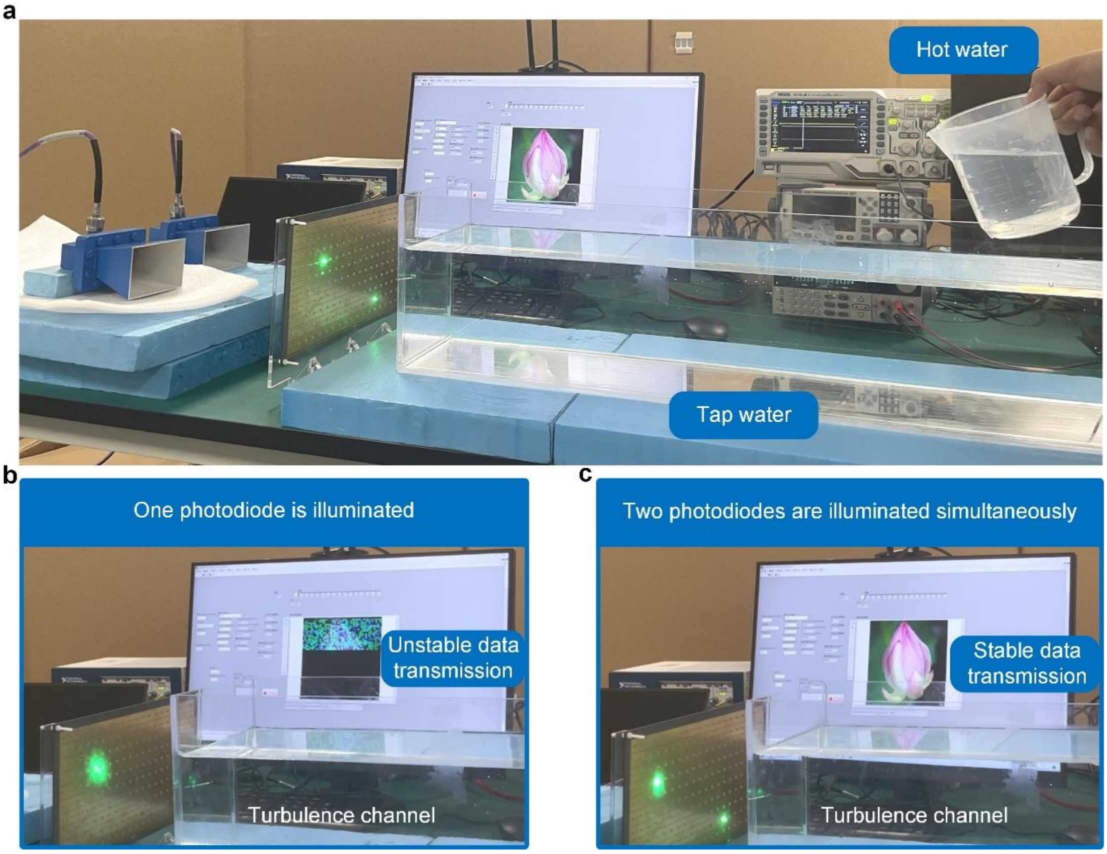


**Fig. R8. Experiments of the wireless transmission across underwater turbulence channel. a**, Photograph of the experimental setup, in which tap water is first injected into the water tank, and then hot water is injected into it from the top to down for generating temperature-induced turbulence. **b**, For the case that one photodiode is illuminated, strong turbulence will cause the laser beam diffusion and drift, which will reduce the transmission quality of the link. **c**, The link can still provide relatively stable data transmission when two photodiodes are illuminated simultaneously, because even though one laser beam is in outage, the another still ensure reliable operation.

[R10] Kaushal, H. & Kaddoum, G. Underwater optical wireless communication. *IEEE Access* **4**, 1518-1547 (2016).

[R11] Vali, Z., Gholami, A., Ghassemlooy, Z., Omoomi, M. & Michelso, D. G. Experimental study of the turbulence effect on underwater optical wireless communications. *Appl. Opt.* **57**, 8314-8319 (2018).

[R12] Liu, W., Jiang, W., Huang, N. & Xu, Z. Experimental investigation of underwater optical wireless communication for correlated SIMO channel under temperature-induced turbulence. *IEEE Photon. J.* **15**, 7302907 (2023).

**According to your suggestions, the corresponding revisions are as below:**

1) In the first paragraph of **Page 9** in the revised manuscript, we have added some details on how metasurface can be controlled by a small laser beam, and we have added **Fig. R7** in the Supplementary Information (**Supplementary Fig. 10**).

"Moreover, based on the parallel design, each photodiode can be illuminated independently to generate the desired microwave reflection. We have measured the microwave reflection amplitudes of the metasurface at 4.45 GHz when photodiodes at different positions were illuminated, and the normalized results are shown in **Supplementary Fig. 10**. It is clear that when photodiodes at other positions are illuminated, the metasurface can generate the same reflection amplitude differences. In addition to illuminating one photodiode, the metasurface can also work well when the both photodiodes are illuminated simultaneously. Therefore, we can use small a laser beam to illuminate precisely and modulate metasurface, and multiple photodiodes also provide possibility for spatial diversity receiving."

2) We have added **Fig. R8** in the revised manuscript (**Fig. 4**), and provided some discussions on how to utilize the metasurface to achieve light spatial diversity for reducing the impact of underwater turbulence on the link (See the third paragraph of **Page 11** in the revised manuscript). We have also added a transmission experiment (**Supplementary Movie 2**).

"We demonstrated that two small laser beams can illuminate both photodiodes simultaneously to modulate the microwave reflections of metasurface. Therefore, on the metasurface, spatial diversity transmission[47,48] can be developed and used to reduce the turbulence-induced underwater optical signal fluctuation. We further experimentally investigate the transmission performance of the metasurface-enabled laser-to-microwave wireless link when underwater turbulence is induced. The experimental setup is shown in **Fig. 4a**. To generate obvious temperature-induced underwater turbulence, 20° tap water was first injected into the water tank, and then 60° hot water was injected into it from the top to down. In experiments, we tested the video transmission quality of the laser-to-microwave link when metasurface is illuminated by one laser signal and two identical laser signals simultaneously, and the transmission results are shown in **Fig. 4b,c**, respectively. For the case that one photodiode is illuminated, strong turbulence will cause the laser beam diffusion and drift in a short period of time, thereby reducing the transmission quality of the link. But when two photodiodes are illuminated simultaneously, the link can still provide relatively stable data transmission, because even though one laser beam is in outage, the another still ensure reliable operation, thus mitigating the impact of underwater turbulence. See **Supplementary Movie 2** for entire transmission process."

## To Reviewer #2

**General Comment:** The authors present a neat idea of a device that will be converting microwave signals to optical as well as encode optical signals onto microwaves. My main two concerns that I want authors to address are below.

**Our Reply:**

We appreciate very much for your very positive comments. You have given us very useful suggestions to improve the quality of our manuscript, and we have addressed you concerns and revised the manuscript accordingly.

**Comment 1:** Make claims more clear. For example, they say that the device does not need power to operate to do conversions. While this is technically true, there is no active elements in the metasurface, the microwave read-out needs an incident microwave signal that carries power. For larger distances, the required power can become too large.

**Our Reply:**

Thank you very much for your helpful suggestion. Typically, for real-time manipulation of EM waves, the programmable metasurfaces require direct-current (DC) power supply and bias circuit to control the operating states of the loaded sensitive materials or components. Thus, the traditional programmable metasurfaces need to be connected to a DC supply to provide driving bias, leading to consuming consumption. In sharp contrast to the traditional schemes, our microwave-optical conversion metasurface does not need to be connected to any DC supply. That is to say, it can operate in a wireless and battery-free mode. Thus, from this perspective, the metasurface do not require a DC source to supply power, and we called it "zero-power" in original manuscript. But as you mentioned, while this is technically true, for the optical-to-microwave conversion, an incident microwave signal is required, and thus the metasurface needs a microwave source. We apologize for not clearly explaining this in the original manuscript.

**According to your suggestions, the corresponding revisions are as below:**

In the revised manuscript, we have used "programmable metasurface without DC supply" to replace "zero-power metasurface", and also have provided more discussion to make the source requirements clearer (See the second paragraph of **Page 6**). And based on this, we have revised the title of the manuscript to "**Wireless microwave-to-optical conversion via programmable metasurface without DC supply**".

"In sharp contrast to traditional diode-based metasurfaces that require power supplies to provide bias voltage for loaded diodes, our microwave-optical interconversion metasurface does not need to be connected to any DC supplies. That is to say, it can operate in a wireless and battery-free mode. Under the microwave incidence, the resonant structure 1 will induce a surface current (**Supplementary Fig. 3**) and then generates a potential across the cathode and anode of the Schottky diode. As the incident microwave power increases, the generated potential difference will be greater than the threshold voltage of the Schottky diode, and it will be driven on[45]. Therefore, the Schottky diode can be switched on for a strong microwave power but remain off for weak incident waves. For the photodiode, it can be used as an optically-controlled capacitor for tuning microwave resonance[18], due to the light-induced space-charge region change. Remarkably, these two mechanisms do not require any external biases, and in essence, there are the microwave signal and laser signal themselves to drive Schottky diode and photodiode."

**Comment 2:** The practicality of this approach is questionable. I think that in the main body of the manuscript they should specify the main performance characteristics. This includes what is the conversion efficiency of the microwave power into optical power - e.g. if I send 1W per square centimeter at microwave frequency, what will be the light output? In figure 1 they have the drawing of the satellite communication utilizing this device. How much microwave power will satellite need to send to Earth in order to then receive the modulated microwave signal? What is the output energy in the laser beam is needed to modulate the microwaves if the object is 100m (or any other distance) underwater?

**Our Reply:**

Thank you very much for your good comments and professional suggestions. We apologize that we did not provide the relevant performance of the metasurface before, which makes the practicality of the metasurface unclear and questionable. To more convincingly demonstrate the potential applications as you suggested, we specify three main performance characteristics of the metasurface.

The first is "*what is the conversion efficiency of the microwave power into optical power - e.g. if I send 1W per square centimeter at microwave frequency, what will be the light output?*", and our responses are as fellows.

The microwave-to-laser conversion efficiency $\eta_c$ is calculated by:

$$\eta_c = \frac{P_r}{P_o} \tag{5}$$

where $P_r$ is the microwave power received by the metasurface, and $P_o$ is the output power of the generated laser. We have provided a schematic of the power transmission process for the microwave-to-optical conversion, as shown in **Fig. R9**. The $P_s$ is the power of microwave source, $G_a$ is the gain of the power amplifier, and $P_{total}$ = $P_s$ + $G_a$ is the total microwave power. The "Input microwave power" in **Fig. 2d** in the original manuscript refers to the total power $P_{total}$. Obviously, the total power is the ideal power of the system, which not only includes the available power, but also includes the power losses caused by coaxial cables, connectors, and free space. When the horn antenna is placed close to the metasurface, the free-space loss can be ignored. Therefore, the received microwave power $P_r$ is equal to ($P_{total}$ - 2$P_{loss}$), which is less than the total power. We have tested the power loss $P_{loss}$ of one used coaxial cable and connector, and it is 3 dB. As shown in **Fig. 2d** in the original manuscript, when the total power $P_{total}$ is 100 mW (20 dBm), the output laser power $P_o$ is 2.7 mW. However, the actual received microwave power $P_r$ is just 25 mW, in this case, the microwave-to-laser conversion efficiency $\eta_c$ is calculated as 10.8%.

We note that the conversion efficiency $\eta_c$ depends on both the rectification efficiency of the metasurface and the electro-optical conversion efficiency of the integrated laser diode. For Schottky diode, it can work well within a certain range of incident microwave power. When the illuminated microwave power is 25 mW, the power density is only 5.6 x $10^{-5}$ W/cm$^2$, which is much lower than 1W/cm$^2$. That is to say, such a high microwave power density will damage the "HSMS-2860" Schottky diode. But we have also tested the conversion efficiencies with increasing microwave power. When the illuminated microwave power is increased to 250 mW (24 dBm), the conversion efficiency $\eta_c$ is 6.48%. In our current design, to reduce power consumption, we have chosen to use a low-power "GH05035A2G" laser diode (from Sharp), and its own electro-optical conversion efficiency is low. Therefore, to improve the conversion efficiency $\eta_c$, an effective approach is to adopt light-emitting diodes with higher electro-optical efficiency. In addition, full-wave rectification scheme could be adopted to increase the rectification efficiency[R13], however, it requires more Schottky diodes compared with current half-wave rectification.

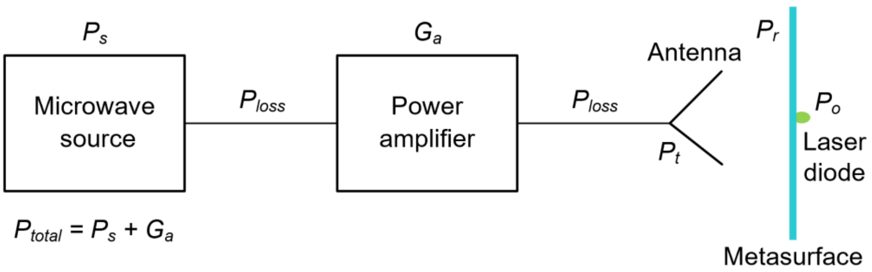


**Fig. R9. Schematic of power transmission process of the microwave-to-optical conversion.** The $P_r$ is the received microwave power by metasurface.

The second is "*In figure 1 they have the drawing of the satellite communication utilizing this device. How much microwave power will satellite need to send to Earth in order to then receive the modulated microwave signal?*", and our responses are as fellows.

Our optical-to-microwave transmission is achieved based on optically-controlled microwave amplitude modulation. That is to say, under different laser intensities, the reflected microwave amplitudes of the metasurface are different, and thus the '0' and '1' data can be sent by switching the back-reflected microwave power. The microwave back-reflected ability of the metasurface can be characterized by its radar cross section (RCS). For amplitude-modulated microwave signal, the difference of the radar cross sections (RCSs) of the metasurface under two different reflection states is[R14]:

$$\Delta\mathrm{RSC} = \frac{\lambda^2}{4\pi} G_m^2 |\Gamma_1 - \Gamma_2|^2 \tag{6}$$

where $G_m$ is the gain of the metasurface; $\Gamma_1$ and $\Gamma_2$ are the microwave power reflection coefficients of the metasurface under two different laser illuminating states, respectively, which can be obtained from meta-element simulation. The gain $G_m$ of the metasurface depends on its effective aperture area $A_\mathrm{m}$, and their relationship is:

$$G_m = \frac{4\pi}{\lambda^2} A_m \tag{7}$$

for planar metasurface at far field, the effective aperture $A_\mathrm{m}$ is equal to its actual physical area. Thus, by substituting **Eq. 7** into **Eq. 6**, we obtain differential radar cross section ΔRSC:

$$\Delta\mathrm{RSC} = \frac{4\pi}{\lambda^2} A_m^2 |\Gamma_1 - \Gamma_2|^2 \tag{8}$$

it is clear that increasing the physical area and reflection coefficient difference of the metasurface helps to improve the ΔRSC, which is more conducive to signal demodulation.

For satellite communication based on the metasurface-enabled reflection amplitude modulation, the received reflected signal power $P_r$ is directly related to the ΔRSC and can be expressed using classical radar equation[R14]:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 d^4} \Delta\mathrm{RSC} \tag{9}$$

where $P_t$ is the microwave power transmitted by the satellite, $G$ is the gain of the satellite antenna, and $d$ is the distance between satellite and metasurface. To demodulate and recover the transmitted data, the received signal power $P_r$ must be greater than the sensitivity of the satellite receiver. From **Eqs. 8 and 9** we know that the received signal power is related to multiple factors, including distance, antenna gain, and metasurface area. As reported in Ref. [R15,R16], the sensitivity of satellite receiver can be as low as -160 dBm, and the antenna gain can reach 50 dBi. In this case, by combining **Eqs. 8 and 9**, we can calculate the required transmitted microwave power for satellite communication. For low earth orbit satellite as we drew in **Fig. 1** in the main text, when the satellite altitude is 2000 km and the metasurface effective area is 300 × 150 $\mathrm{mm}^2$, the calculated required minimum transmitted microwave power is 1.4 W. To reduce the transmitted power, we can increase the metasurface area by using more meta-elements.

The final is "*What is the output energy in the laser beam is needed to modulate the* *microwaves if the object is 100m (or any other distance) underwater?*", and our responses are as fellows.

For the optical-to-microwave conversion, the required illuminated laser power $P_{laser}$ is 21.6 mW (13.3 dBm), as discussed in the original manuscript. Due to the attenuation effects of water to light transmission, to achieve a longer underwater optical wireless communication distance, it is necessary to increase the laser power. As discussed in Ref. [R10], the attenuation rate of blue or green light is approximately 0.39 dB/m in clear ocean. Therefore, we can calculate the required output laser power for different underwater communication distances. When the object is 10 m underwater, the required laser power is about 52.5 mW (17.2 dBm), and when optical communication distance increases to 50 m, the required laser power is about 1910 mW (32.8 dBm), which is comparable to the power levels required for current underwater wireless optical communications[R10]. As the distance increases further to achieve extremely long-distance underwater optical communication, the required power will significantly increase. Recently, several solutions have been proposed to improve the distance of underwater wireless optical communication, such as using spatial diversity techniques and optical lenses. Specifically, it is feasible to install multiple photosensors and combine their signals to increase the sensitivity, and it is also feasible to use large lens over the photosensors to gather more optical power.


[R13] Erkmen, F., Almoneef, T. S. & Ramahi, O. M. Electromagnetic energy harvesting using full-wave rectification. *IEEE Trans. Microw. Theory Techn.* **65**, 1843-1851 (2017).

[R14] Nikitin, P. V., Rao, K. V. S. & Martinez, R. D. Differential RCS of RFID tag. *Electron. Lett.* **43**, 431-432 (2007).

[R15] Kumari, A. & Bhatt, D. Advanced system analysis and survey on the GPS receiver front end. *IEEE Access* **10**, 24611-24626 (2022).

[R16] Rao, S. K. Advanced antenna technologies for satellite communications payloads. *IEEE Trans. Antennas Propag.* **63**, 1205-1217 (2015).


**According to your suggestions, the corresponding revisions are as below:**

1) We have provided the microwave-to-optical conversion efficiency of the metasurface and also made discussions in the revised manuscript (See second paragraph of **Page 8** and "**Experiments on microwave-laser conversion**" Section of **Page 14**).

"When the input microwave power reaches 14 dBm (25 mW), the laser diode has been lit and the output laser power is 2.7 mW. Thus, the microwave-to-laser conversion efficiency is calculated as 10.8%. When the input microwave power is increased to 24 dBm (250 mW), the output laser power reaches 16.2 mW, and then the conversion efficiency is 6.48%. The difference in conversion efficiency is due to the fact that Schottky diode and laser diode are intensity-dependent nonlinear components. In our design, to reduce power consumption, we have chosen to use a low-power "GH05035A2G" laser diode (from Sharp), and its own electro-optical conversion efficiency is low. Therefore, to improve the microwave-to-laser conversion efficiency, an effective approach is to use light-emitting diodes with higher electro-optical efficiency. In addition, full-wave rectification scheme could be adopted to increase the rectification efficiency[46], however, it requires more Schottky diodes compared with current half-wave rectification."

"The horn antenna with gain of 15 dBi was fixed 0.1 m away from the metasurface sample, and thus the microwave transmission efficiency is 99.9% (see **Supplementary Note 4** for more details). In this case, the microwave power radiated by the horn antenna is almost completely received by the metasurface. Thus, when the input microwave power reaches enough intensity of 25 mW, the corresponding illuminated power density is about 0.056 $mW/cm^2$. The microwave-to-laser conversion efficiency is defined as the ratio of the output laser power to the microwave power received by the metasurface."

2) We have added some discussions on the required transmitted microwave power for metasurface-based satellite communication in the Supplementary Information (See the first and second paragraphs of **Supplementary Note 9**).

"**Supplementary Note 9. Metasurface-enabled satellite communication and underwater long-distance wireless communication**

As we drew in **Fig. 1** in the main text, the bidirectional conversion metasurface offers an effective wireless platform to link the satellite and underwater equipment. We provide more discussion on this potential application scenario. The Optical-to-microwave transmission is achieved based on the optically-controlled microwave amplitude modulation. That is to say, under different laser intensities, the reflected microwave amplitudes of the metasurface are different, and thus the '0' and '1' data can be sent by switching the back-reflected microwave powers. The microwave reflection ability of the metasurface can be characterized by its radar cross section (RCS). For amplitude-modulated microwave signal, the difference of the radar cross sections (RCSs) of the metasurface under two different reflection states is[10]:

$$\Delta\mathrm{RSC} = \frac{\lambda^2}{4\pi} G_m^2 |\Gamma_1 - \Gamma_2|^2 \quad \text{(S5)}$$

where $G_m$ is the gain of the metasurface; $\Gamma_1$ and $\Gamma_2$ are the microwave power reflection coefficients of the metasurface under two different laser illuminating states, respectively, which can be obtained from the meta-element simulation. The gain $G_m$ of the metasurface depends on its effective aperture $A_\mathrm{m}$, and their relationship is:

$$G_m = \frac{4\pi}{\lambda^2} A_m \quad \text{(S6)}$$

for planar metasurface at far field, the effective aperture $A_\mathrm{m}$ is equal to its actual physical area. Thus, by substituting **Eq. (S6)** into **Eq. (S5)**, we obtain differential radar cross section ΔRSC:

$$\Delta\mathrm{RSC} = \frac{4\pi}{\lambda^2} A_m^2 |\Gamma_1 - \Gamma_2|^2 \quad \text{(S7)}$$

it is clear that increasing the physical area and reflection coefficient difference of the metasurface helps to improve the ΔRSC, which is more conducive to signal demodulation.

For satellite communication based on the reflection amplitude modulation, the received signal power $P_r$ by the satellite is directly related to the ΔRSC and can be expressed using classical radar equation[10]:

$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 d^4} \Delta\mathrm{RSC} \quad \text{(S8)}$$

where $P_t$ is the microwave power transmitted by the satellite, $G$ is the gain of the satellite antenna, and $d$ is the distance between satellite and metasurface. To demodulate and recover the transmitted data, the received signal power $P_r$ must be greater than the sensitivity of the satellite receiver. From **Eq. (S7)** and **Eq. (S8)**, we know that the received signal power is related to multiple factors, including distance, antenna gain, and metasurface area. As reported in **Supplementary Ref. 11,12**, the sensitivity of satellite receiver can be as low as -160 dBm, and antenna gain can reach 50 dBi. In this case, by combining **Eq. (S7)** and **Eq. (S8)**, we can calculate the required transmitted microwave power for the metasurface-based satellite communication. When the satellite altitude is 2000 km and the metasurface effective area is 300 × 150 $\mathrm{mm}^2$, the calculated minimum satellite transmitted microwave power is about 1.4 W. To reduce the transmitted power, we can increase the metasurface area by using more meta-elements."

3) We have added some discussions on the required laser powers for different underwater wireless optical communication distances in the Supplementary Information (See the third paragraph of **Supplementary Note 9**).

"For the optical-to-microwave conversion, the required illuminated laser power $P_{laser}$ is 21.6 mW (13.3 dBm), as discussed in the main text. Due to the attenuation effect of water to light transmission, to achieve a longer underwater optical wireless communication distance, it is necessary to increase the laser power. As discussed in **Supplementary Ref. 13**, the attenuation rate of blue or green light is approximately 0.39 dB/m in clear ocean. Therefore, we can calculate the required laser power for different underwater communication distances. When the object is 10 m underwater, the required laser power is about 52.5 mW (17.2 dBm), and when optical communication distance increases to 50 m, the required laser power is about 1910 mW (32.8 dBm), which is comparable to the power levels required for current underwater wireless optical communications[13]. As the distance increases further to achieve extremely long-distance underwater optical communication, the required power will significantly increase. Recently, several solutions have been proposed to improve the underwater wireless optical communication distance, such as spatial diversity techniques and optical lenses. Specifically, it is feasible to use multiple photosensors and then combine their receiving signals to increase the sensitivity, and it is also feasible to use large lens over the photosensors to gather more optical power."

**Comment 3:** Zero-power and battery-free in the same sentence is not needed. "enough intensity" - please define.

**Our Reply:**

Thank you very much for your kind reminder and good suggestions. In Abstract of the original manuscript, we state that "Here, we propose a zero-power metasurface, which can achieve direct and high-speed free-space microwave-to-laser conversion on a battery-free ultrathin platform." As you pointed out that zero-power and battery-free in the same sentence is not needed. You are right. Because in our design, zero-power and battery-free both mean that the metasurface does not need to be connected to any external voltage source. In Abstract of the revised manuscript, this sentence has been revised as "Here, we propose a programmable metasurface that can achieve direct and high-speed free-space microwave-to-laser conversion."

For microwave-to-optical conversion, the incident microwave power must be sufficient to light up the laser diode. In our experiment, the integrated green laser diode was lit when the illuminated microwave power density reached 0.056 mW/cm$^2$. Therefore, "enough intensity" refers to illuminated microwave power density up to 0.056 mW/cm$^2$.

**According to your suggestions, the corresponding revisions are as below:**

We have clearly defined "enough intensity" in the "**Experiments on microwave-laser conversion**" Section in the revised manuscript.

"Thus, when the input microwave power reaches enough intensity of 25 mW, the corresponding illuminated power density is about 0.056 $mW/cm^2$."

**Comment 4:** "Very fast" is relative, and "hundreds of kHz" is not that fast in some applications.

**Our Reply:**

Thank you very much for your kind reminder and good suggestion. In the current demonstration, we have realized 400 and 100 kbps data rates over the microwave-to-laser and laser-to-microwave transmission links, respectively, based on the metasurface that does not require any voltage sources. We have also verified that these rates can be used for video transmission in air-water cross-media interface. Thus, in the original manuscript, we would want to indicate that for battery-free platforms, the communication rate is high. But as you mentioned, "very fast" is relative, because faster communication rates can be achieved on active systems with external voltage source.

**According to your suggestions, the corresponding revisions are as below:**

In the second paragraph of **Page 4** in the revised manuscript, we have revised the description of the link rate to make it more accurate.

"Importantly, even there is no power supply connection, the switching speed of the metasurface reaches the level of hundreds kHz."

**Comment 5:** For simulations, authors use "when the Schottky diode operates in the on state". The "on" state for a diode means that it is positively biased, which means that there should be a source of voltage applied to it. However authors do not have this - please write this section more clearly.

**Our Reply:**

Thank you very much for your careful reading and good suggestion. When the

Schottky diode operates in the on state, it does require a forward bias to drive it. However, unlike conventional biasing methods that the voltage comes from an external wired power supply, the bias for the Schottky diode is provided by wireless incident microwaves. For our meta-element design, the Schottky diode is integrated between two metal patches of the microwave resonant structure 1. When the microwave propagates into the meta-element, the resonant structure 1 will induce a surface current**.** Then, the induced surface current will generate a potential across the cathode and anode of the Schottky diode[R17]. Unlike other diodes, Schottky diode contains a MS junction with low forward voltage drop. Therefore, as the microwave power increases, the generated potential difference will be greater than the threshold voltage of the Schottky diode, and it will be driven on. That is to say, the Schottky diode is switched on by incident microwaves.

[R17] Phon, R & Lim, S. Dynamically self-reconfigurable multifunctional all-passive metasurface. *ACS Appl. Mater. Interfaces* **12**, 42393-42402 (2020).

**According to your suggestions, the corresponding revisions are as below:**

We have added some discussions on how to drive the Schottky diode in the revised manuscript (See the second paragraph of **Page 6**).

"Under the microwave incidence, the resonant structure 1 will induce a surface current (**Supplementary Fig. 3**) and then generates a potential across the cathode and anode of the Schottky diode. As the incident microwave power increases, the generated potential difference will be greater than the threshold voltage of the Schottky diode, and it will be driven on[45]. Therefore, the Schottky diode can be switched on for a strong microwave power but remain off for weak incident waves. For the photodiode, it can be used as an optically-controlled capacitor for tuning microwave resonance[18], due to the light-induced space-charge region change. Remarkably, these two mechanisms do not require any external biases, and in essence, there are the microwave signal and laser signal themselves to drive Schottky diode and photodiode."

**Comment 6:** Phrases like "When spatial laser is incident on the meta-element" are a bit ambiguous. What laser is called spatial? What does it mean the laser is incident (sounds like the laser is thrown onto meta-element)

**Our Reply:**

Thank you very much for your careful reading and good suggestions. For the metasurface-based optical-to-microwave conversion, the laser signal propagates in free space, rather than relying on fibers. Therefore, we called it “spatial laser” in the original manuscript. And the “laser is incident” means the laser signal propagates into the meta-element to modulate its microwave reflections. But as you mentioned, it is a bit ambiguous.

In the revised manuscript, we have modified the corresponding descriptions to make expressions clearer and more accurate, and we also checked thoroughly the whole manuscript to make it more readable, as you suggested.

# Responses to Reviewers' Comments

We thank both reviewers very much for reviewing the revised version of our manuscript. We sincerely appreciate the further constructive comments, which help us improve the quality of the manuscript, and we have revised the manuscript accordingly. The revised part is highlighted in **blue fonts** in the revised manuscript. Below are our detailed responses.

## To Reviewer #1

**General Comment:** The authors have addressed convincingly all my comments.

**Our Reply:**

Thank you very much for your positive feedback and kind support.

## To Reviewer #2

**General Comment:** I thank the authors for responding to my comments. They answered all my questions well.

**Our Reply:**

Thank you very much for your positive feedback and kind support.

**Comment 1:** Probably The eq 5 in response is upside-down? Otherwise the efficiency would always be greater than 1.

**Our Reply:**

Thank you very much for your careful reading and kind reminder. You are right. Due to a typo, the numerator and denominator of the equation of the conversion efficiency $\eta_c$ were inadvertently reversed in the original response letter. The correct conversion efficiency $\eta_c$ should be represented as:

$$\eta_c = \frac{P_o}{P_r} \tag{1}$$

where $P_r$ is the microwave power received by the metasurface, and $P_o$ is the output power of the generated laser. In our revised manuscript, all conversion efficiencies were calculated using the above correct equation.

**Comment 2:** I am still a bit confused how the Shottky diode becomes positively biased under the RF signal. The diode conducts during the positive cycle of RF signal, and does not conduct during negative part of the cycle of RF signal. This creates negative voltage on the diode. So the bias should be negative, i.e. the diode in off state?

**Our Reply:**

Thank you for your thoughtful inquiry regarding the operation of a Schottky diode under an RF signal. For RF signal input, Schottky diodes do not always operate under forward bias state. Typically, the bias refers to the steady-state direct-current voltage applied to the diode to set its initial operating point, whereas the instantaneous voltage varies with the RF signal's oscillations. In an RF signal, the voltage is constantly changing. Therefore, the Schottky diode experiences both forward and reverse biases instantaneously as the signal cycles. As you pointed out, the Schottky diode conducts during the positive portion of the RF cycle (forward bias) and does not conduct during the negative portion (reverse bias). That is to say, under RF signals, the on and off states of Schottky diodes change instantaneously. Therefore, for a single Schottky diode, the rectification efficiency is usually less than 50%.

We have added some discussions on instantaneous state of the Schottky diode in the revised manuscript (See the second paragraph of **Page 6**).

"We note that under the microwave incidence, the Schottky diode experiences both forward and reverse biases instantaneously as the microwave signal cycles. That is to say, the Schottky diode conducts during the positive cycle of microwave signal, and does not conduct during the negative cycle of microwave signal."

**Comment 3:** I still think that the English needs improvement for readability, and hope that the editorial office can help with this.

**Our Reply:**

Thank you for your constructive feedback on the readability of the manuscript. We have carefully revised the text to enhance its clarity and readability, ensuring that the language is concise and easy to understand. We also appreciate very much any additional support or guidance the editorial office could provide in this regard.