

Million-Q Free Space Meta-Optical Resonator at Near-Visible Wavelengths

Corresponding Author: Dr Jie Fang

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)

Jie Fang and colleagues have developed a million-Q metasurface in the near-visible regime. To achieve this, they use an etch free design. The manuscript is fairly complete with theory and experiment and is well-written. While million-Q metasurfaces have been shown in the near and mid infrared regime, to the best of my knowledge, this is a record Q for a metasurface in the near-visible regime and as such I support publication of this work in Nature Communications.

Major comment:

1. The authors target 779 nm due to what they have available in their lab, but this is in the near-IR regime and not the visible regime. This should be corrected to near visible or near IR in the title throughout the paper.

Minor revision:

1. The authors mention that: "At visible wavelengths, million-scale (10^6) Q-factors have been accessed in integrated photonic resonators, such as micro-ring and micro-disk cavities^{9,1}" Recently, however, microtoroids have also demonstrated over a million Q using free space optics: <https://www.nature.com/articles/s41377-024-01418-0>

Reviewer #2

(Remarks to the Author)

The authors have demonstrated a guided mode resonator at visible wavelengths with Q of a million. This advance is characterized using a scanning momentum-resolved spectroscopy, and combined with WSe₂ integration to show the impact of the high Q on narrowed emission from a layer.

This paper reports a noteworthy advance (million Q at visible wavelength, with coupled TMD) that would be of interest to the large photonics and materials community. Achieving ultra-high Q in most situations is noteworthy, and doing it here with the novel etchless design is exciting. The results are technical (an achievement that solves a challenge, rather than new understanding of the system), but the impact potential is significant, broadly appreciable, and in my opinion quite appropriate for Nature Communications. Alongside this technical quality, the manuscript is clearly written, understandable, and strongly supported by ample data and detailed supplementary information. I recommend publication.

Some additional technical comments:

1. The discussion of WSe₂ was motivated as looking at the advantages of the ultrahigh Q platform. The following discussions are succinct observations. It felt like this section was lacking in a takeaway message. Are these ultrahigh Q observations notable? How do they compare with prior high Q emission measurements? Is there any notable advantage here? Does the ultrahigh Q solve a challenge with the material? The summary/conclusion implies it may, but the discussion itself does not strongly connect the observations to their context.

2. For the momentum space imaging, the collection-side polarizer is fixed and the excitation polarizer is rotated. Is there a significant dependence of results on this orientation, or is it just noise suppression/optimization? The same setting is used throughout, but does this optimum not change with laser scanning or focus?

3. I did not find a reference to Figure S11 in either SI or main text. This is an easy thing to add for clarity of how to interpret the figure.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

The reviewer comments were all quite positive in the prior round, and the authors have addressed the minor comments. This should be accepted for publication.

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Dear Editor and Reviewers,

Thank you for your valued time in handling and evaluating our manuscript entitled "Million-Q Free Space Meta-Optical Resonator at **Near-Visible** Wavelengths" (NCOMMS-24-55673-T).

We sincerely thank the Reviewers for the positive evaluation of our work and the constructive comments which helped to improve our manuscript.

Please, find below a detailed point-by-point response to the Reviewers' questions and suggestions. All the modifications related to technical contents are highlighted in **RED** in the revised copies of manuscript and supplementary information.

Sincerely yours,

Arka Majumdar (for all the authors)
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REPLY TO THE REVIEWER #1

Jie Fang and colleagues have developed a million-Q metasurface in the near-visible regime. To achieve this, they use an etch free design. The manuscript is fairly complete with theory and experiment and is well-written. While million-Q metasurfaces have been shown in the near and mid infrared regime, to the best of my knowledge, this is a record Q for a metasurface in the near-visible regime and as such I support publication of this work in Nature Communications.

Author reply: We sincerely thank the Reviewer for the positive evaluation of our work and the valuable comments.

Comment 1: The authors target 779 nm due to what they have available in their lab, but this is in the near-IR regime and not the visible regime. This should be corrected to near visible or near IR in the title throughout the paper.

Author reply: We thank the Reviewer for the constructive comment. We agree with the Reviewer and decide to use the term ‘near-visible’ as the Reviewer suggested. Modifications have been made in the title and throughout the manuscript when we mentioned the million Q-factor.

Comment 2: The authors mention that: “At visible wavelengths, million-scale (10^6) Q-factors have been accessed in integrated photonic resonators, such as micro-ring and micro-disk cavities^{9,1}” Recently, however, microtoroids have also demonstrated over a million Q using free space optics: <https://www.nature.com/articles/s41377-024-01418-0>.

Author reply: We thank the Reviewer for bringing this important reference into our attention. We have cited it in our introduction section as Ref.[15] and modified the related sentences on Page 3:

(Main text Page 3) “At visible wavelengths, million-scale (10^6) Q-factors have been accessed in *individual* photonic resonators such as *evanescently-coupled* micro-ring and micro-disk cavities^{1,14}, and *free-space-coupled microtoroids*¹⁵.”

REPLY TO THE REVIEWER #2

The authors have demonstrated a guided mode resonator at visible wavelengths with Q of a million. This advance is characterized using a scanning momentum-resolved spectroscopy, and combined with WSe₂ integration to show the impact of the high Q on narrowed emission from a layer.

This paper reports a noteworthy advance (million Q at visible wavelength, with coupled TMD) that would be of interest to the large photonics and materials community. Achieving ultra-high Q in most situations is noteworthy, and doing it here with the novel etchless design is exciting. The results are technical (an achievement that solves a challenge, rather than new understanding of the system), but the impact potential is significant, broadly appreciable, and in my opinion quite appropriate for Nature Communications. Alongside this technical quality, the manuscript is clearly written, understandable, and strongly supported by ample data and detailed supplementary information. I recommend publication.

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Comment 1: The discussion of WSe₂ was motivated as looking at the advantages of the ultrahigh Q platform. The following discussions are succinct observations. It felt like this section was lacking in a takeaway message. Are these ultrahigh Q observations notable? How to they compare with prior high Q emission measurements? Is there any notable advantage here? Does the ultrahigh Q solve a challenge with the material? The summary/conclusion implies it may, but the discussion itself does not strongly connect the observations to their context.

Author reply: We thank the Reviewer for the constructive comments. It helps improve our manuscript a lot. We have added additional discussions to highlight the notable advantages of our ultrahigh-Q platform in the WSe₂ emission section on Pages 15, 16, 18:

(Main text Page 15) “... a highly unidirectional and narrow-linewidth exciton emitter at room temperature *beyond the intrinsic material limitation.*”

(Main text Page 16) “... (FWHM) spectral linewidth (Γ_λ) of ~25.12 nm and *shows very*

poor directivity with a FWHM linewidth in far-field emission angle (Γ_θ) of $\sim 120.95^\circ$... ”

“... which reveal the highly concentrated emission at the Γ point of GMR. Such achievement enables the practical applications of 2D TMD materials in displays and optical communications. We emphasize that, compared to the 2D material integration with nanostructured cavities, our approach of sandwiching TMDs between two thin layers can be well extended to large-scale integration with chemical vapor deposition (CVD)-grown layered materials.”

(Main text Page 18) “..., suggesting amplified spontaneous emission (ASE) in our system because of the extremely high density of state at the Γ point thanks to the record-high Q-factors.”

Comment 2: For the momentum space imaging, the collection-side polarizer is fixed and the excitation polarizer is rotated. Is there a significant dependence of results on this orientation, or is it just noise suppression/optimization? The same setting is used throughout, but does this optimum not change with laser scanning or focus?

Author reply: We thank the Reviewer for the critical questions.

(1) The collection-side polarizer determines the result (type of mode) one wants to measure, while the excitation-side polarizer is only for noise suppression and optimization purpose.

(2) This is a very good question. We found that the optimized excitation-side polarizer orientation can slightly change at different wavelengths (laser scanning) and at different focuses (small changes) when we go through multiple devices on an $8 \times 8 \text{ mm}^2$ chip. It is because both wavelengths and optical light path length influence the unwanted interference pattern background/noise.

However, the influence is small as long as the whole optical setup is kept unchanged. Therefore, for the consistency of the whole measurements, we do not change the excitation-side polarizer orientation once fixed.

We have added this discussion to supplementary information Note 3 on Page 9.

Comment 3: I did not find a reference to Figure S11 in either SI or main text. This is an easy thing to add for clarity of how to interpret the figure.

Author reply: We thank the Reviewer for the constructive suggestion. We have added a reference to Figure S11 in the Methods on Page 24:

(Main text Page 24) “..., a slightly deviated device period P of 504 nm is applied. *The SEM images can be found in Supplementary Fig. S11.*”