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Single-source chip-based frequency comb enabling extreme parallel data transmission

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Single-Source Chip-based Frequency Comb Enabling Extreme Parallel Data Transmission

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1. Group velocity dispersion (GVD) for the AlGaAsOI nano-waveguide

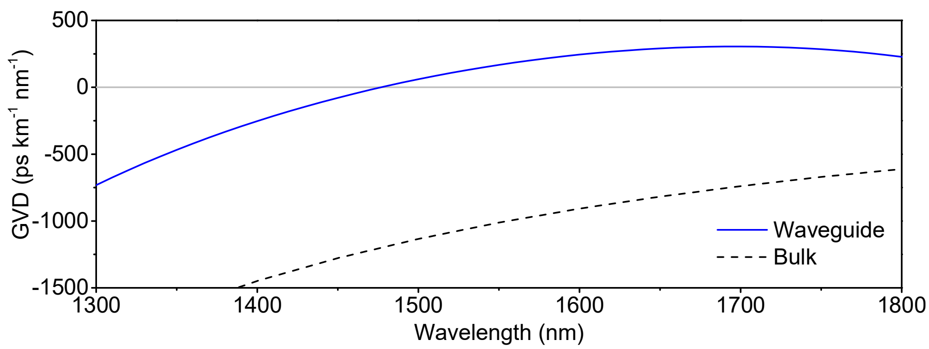


Fig. S1. Calculated group velocity dispersion (GVD) versus wavelength for the waveguide with 280 nm×600 nm cross-section dimension. The dashed curve shows the GVD for bulk AlGaAs material.

2. Linewidth measurements for the broadened frequency comb

A delayed self-heterodyne method was used to measure the linewidth of the broadened frequency comb, with the experimental setup shown in Fig. S2A. A tunable narrowband filter (0.1 nm full width at half maximum, FWHM) was used to select one of the tones of the frequency comb. The selected tone was amplified and split into two branches. In the upper branch the light passed through a 35 km fiber delay and in the lower branch the light passed through an acoustic-optical modulator (AOM) to shift the center frequency by 27 MHz. The delayed light and the non-delayed light with frequency shifting generate a beat note centered at 27 MHz, which is measured using an electrical spectrum analyzer. The measured electrical spectra are shown in Fig. S2B for three cases: seeded mode-locked laser centered at 1542 nm, broadened frequency comb at 1529.97 nm and 1560.09 nm. All these cases have a measured linewidth of 40 kHz (with a resolution bandwidth of 10 kHz), using a Lorentzian line shape fitting.

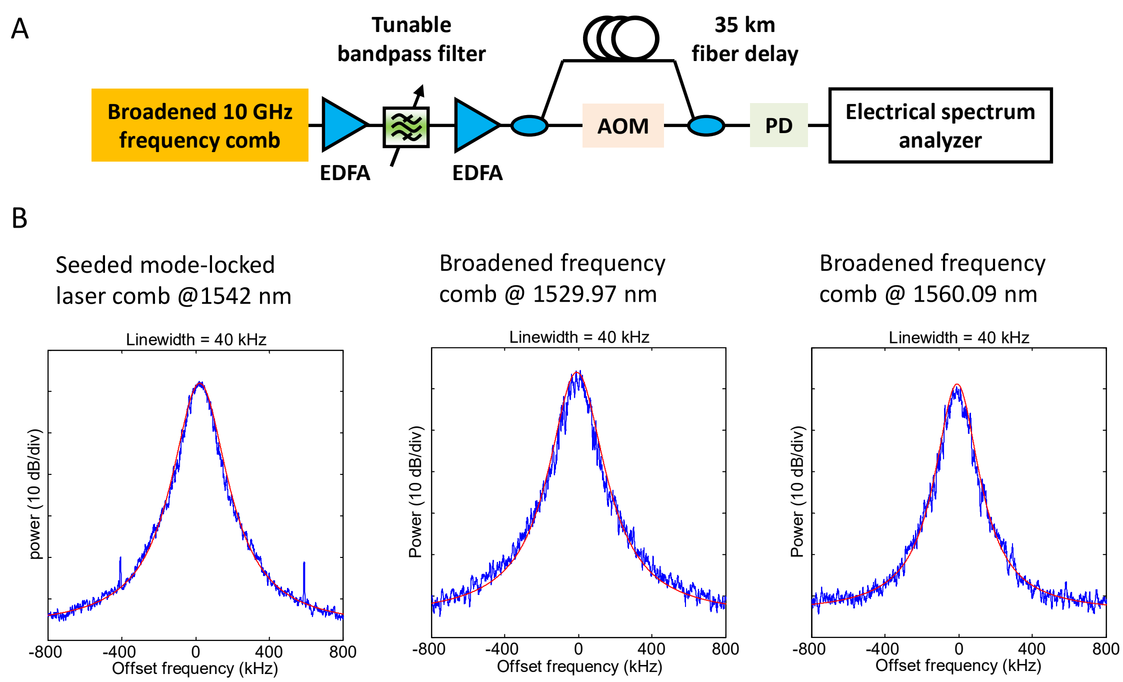


Fig. S2. Linewidth measurement for broadened frequency comb. (A) Experimental setup of delayed self-heterodyne method for the linewidth measurement. (B) Beat note with Lorentzian line shape fitting for seeded mode-locked laser frequency comb at 1542 nm, broadened frequency comb at 1529.97 nm and 1560.09 nm.

3. Relative intensity noise (RIN) measurements

We have measured the RIN of the broadened frequency comb by using an HP 71400C Lightwave Signal Analyzer. Three tones of the broadened frequency comb at 1529.97 nm, 1551.97 nm and 1560.09 nm are sequentially filtered, amplified and then measured, as shown in Fig. S3. The pump laser at 1542 nm is also measured as the reference after the filtering and amplifying. Since the bandpass filters used in the experiment cannot completely filter out the two neighboring 10-GHz spacing tones, the 10-GHz and 20-GHz beating note can be seen in the measurement. At the high frequency above 20 GHz, all these three cases have RIN of around -142 dB/Hz, which is same as the reference. At the low frequency regime, the RIN of the frequency tones at 1529.97 nm and 1560.09 nm is higher than the reference mainly due to the OSNR degradation at the edge of the broadened frequency comb. The RIN of the frequency tone at 1551.97 nm is very close to the reference since it is at the peak of the broadened frequency comb and has a high OSNR.

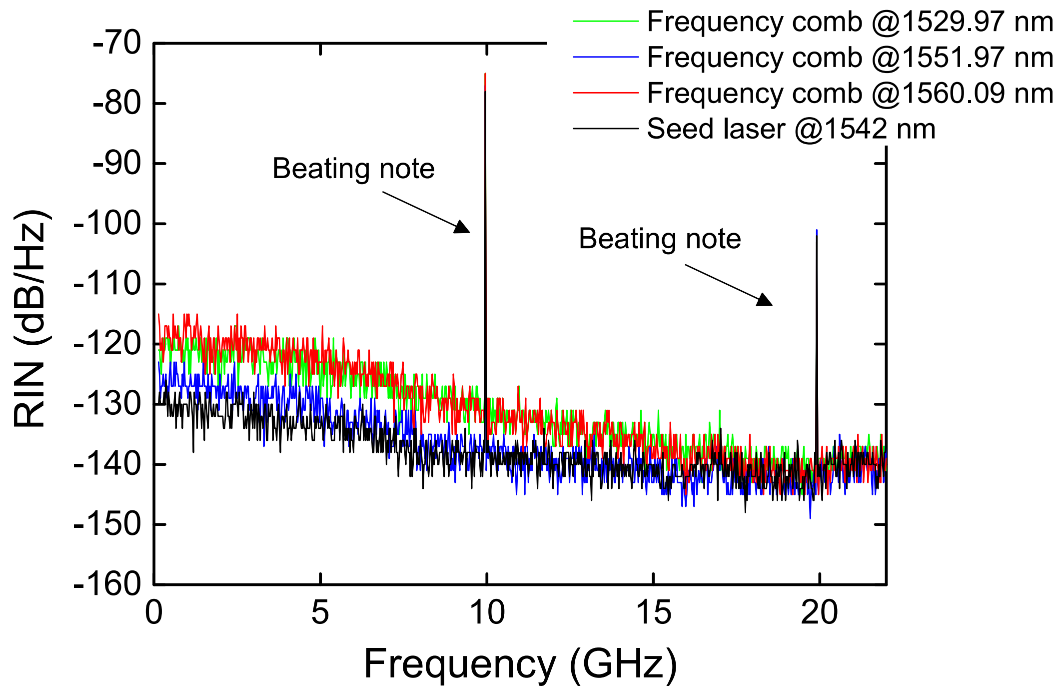


Fig. S3. RIN measurements for the pump laser at 1542 nm and the broadened frequency comb at 1529.97 nm, 1551.97 nm and 1560.09 nm, respectively. 10 GHz and 20 GHz beating notes are generated by the neighboring comb lines due to imperfect filtering.

4. Frequency noise measurements

We have measured the frequency noise spectrum for the 10 GHz pump laser at 1542 nm and the broadened frequency comb at 1550.05 nm. The measurement is based on coherent heterodyne detection[1], where the laser under test beats with a low-noise fiber laser[2]. The experimental setup is shown in Fig. S4A. The instantaneous phase Φ is extracted from the recovered electrical field *E* using the forth quadrant arctangent:

$$E(t) = E_I(t) + jE_Q(t) \tag{1}$$

$$\Phi = \arctan\frac{E_Q(t)}{E_I(t)} \tag{2}$$

The derivative of the instantaneous phase Φ gives the instantaneous frequency:

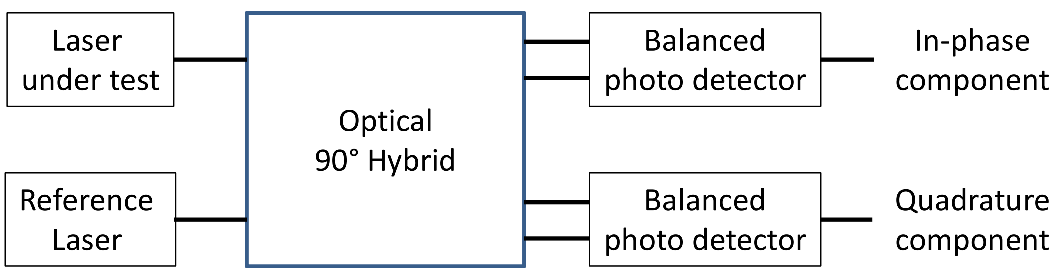
$$\nu[k] = \frac{\Phi[k] - \Phi[k-1]}{2\pi\Delta t} \tag{3}$$

where $\Delta t = 1 / F_s$ with $F_s = 250$ MHz being the sampling frequency. The measurement time was set to 100 ms, corresponding to a frequency resolution of 10 Hz. Finally, the frequency noise spectrum $F_N(f)$ is calculated as:

$$F_N(f) = \frac{1}{t[N] - \Delta t} \cdot |FFT(\nu)\Delta t|^2 \tag{4}$$

with $FFT(\cdot)$ being the fast Fourier transform of $\cdot$ and $t[N]$ being the last instant of the temporal window. Afterwards, a moving average filter with a length of 5 is applied to smoothen out measurement noise and the frequency noise spectrum is shown in Fig. S4B.

A



B

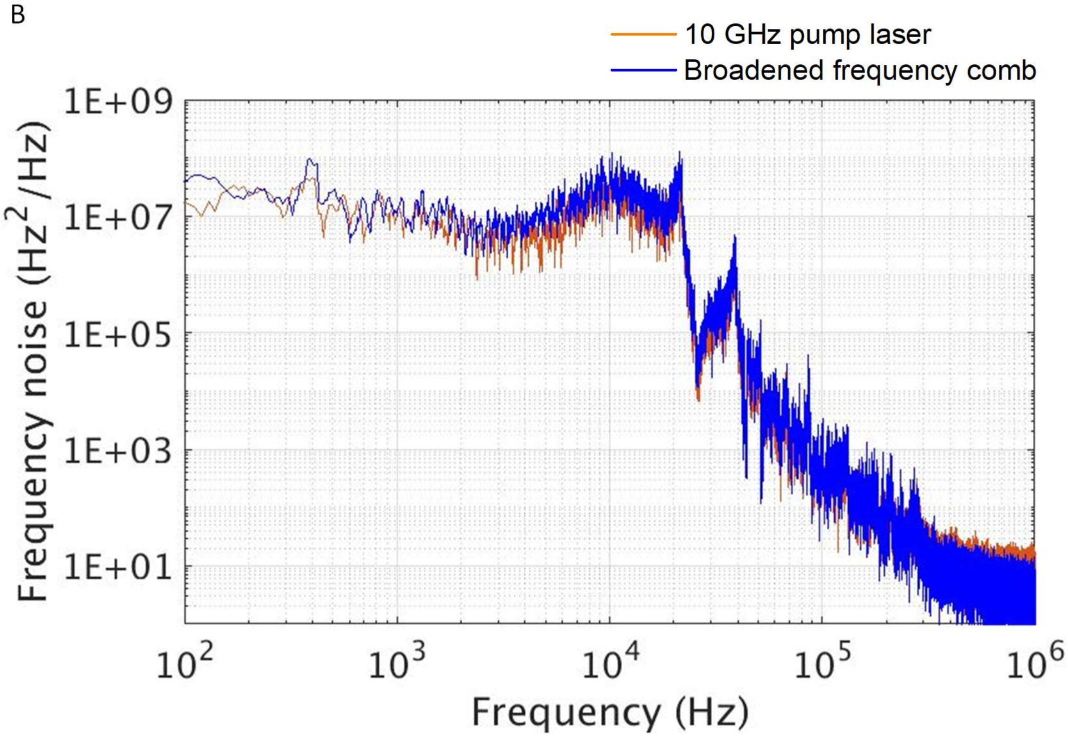


Fig. S4. Frequency noise measurements. A. Experimental setup based on coherent heterodyne detection. B. Measured frequency noise spectrum for the 10 GHz pump laser and the broadened frequency comb at 1550.05 nm.

5. RF beat note of the broadened frequency comb

The whole broadened frequency comb at the output of the AlGaAs chip is detected by a 50-GHz photodiode and the RF beat note is measured by a radio frequency (RF) spectrum analyzer, as shown in Fig. S5A. The RF linewidth of the 10 GHz beat note is measured to be 1 Hz (with a limited resolution bandwidth of 1 Hz). The single side band (SSB) phase noise of the 10 GHz beat note is measured for the 10 GHz mode-locked pump laser and the broadened frequency comb, as shown in Fig. S5B. The phase noise of the broadened frequency comb is almost same as that of the 10 GHz mode-locked pump laser, indicating that the frequency comb broadening process did not introduce extra noise.

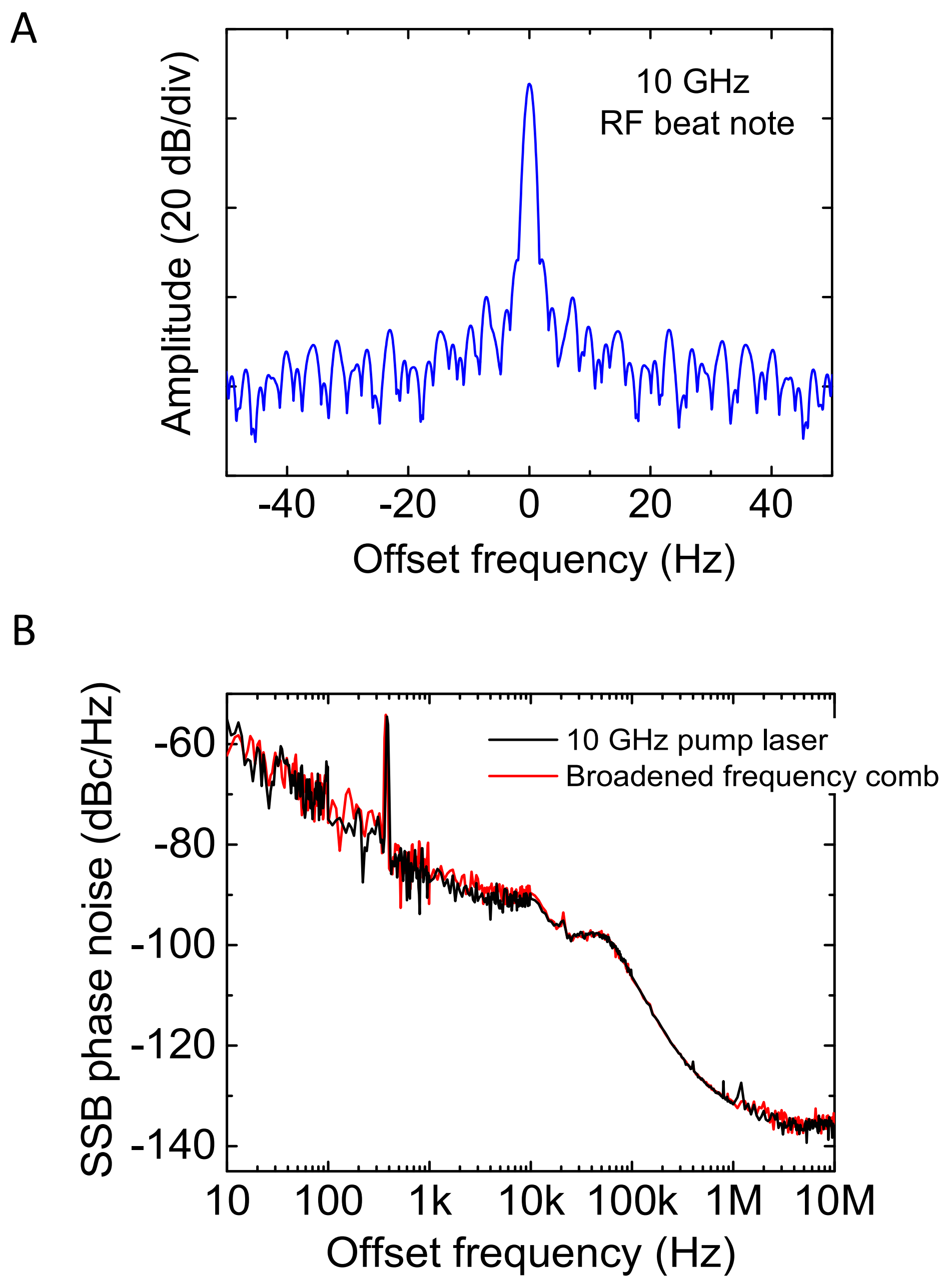


Fig. S5. Measurements of radio frequency (RF) beat note of the whole broadened frequency comb at the output of the AlGaAs chip. A. Measured RF beat note of the broadened frequency comb. B. Measured single side band (SSB) phase noise of the RF beat note for the 10 GHz mode-locked pump laser and the broadened frequency comb.

6. Frequency comb broadening with temperature varying

The frequency comb broadening is based on self-phase modulation in the non-resonant nano-waveguide, which is insensitive to the temperature change. In order to test the temperature tolerance of the chip-based frequency comb broadening, we measured the broadened frequency comb at the output of the AlGaAs chip under different temperatures. The coupling between the tapered fiber and the AlGaAsOI nano-waveguide was optimized during the temperature changing in order to keep high coupling efficiency. As shown in Fig. S6, the envelopes of the broadened frequency combs are almost the same for various temperatures of 20°, 25°, 30° and 34°. The under-test temperatures are limited by the range of the available temperature controller. The small variance of the broadened frequency combs under different temperatures is mainly attributed to the slightly different coupling conditions. The optical spectra of the broadened frequency combs are measured by an optical spectrum analyzer with a resolution bandwidth (RBW) of 0.1 nm.

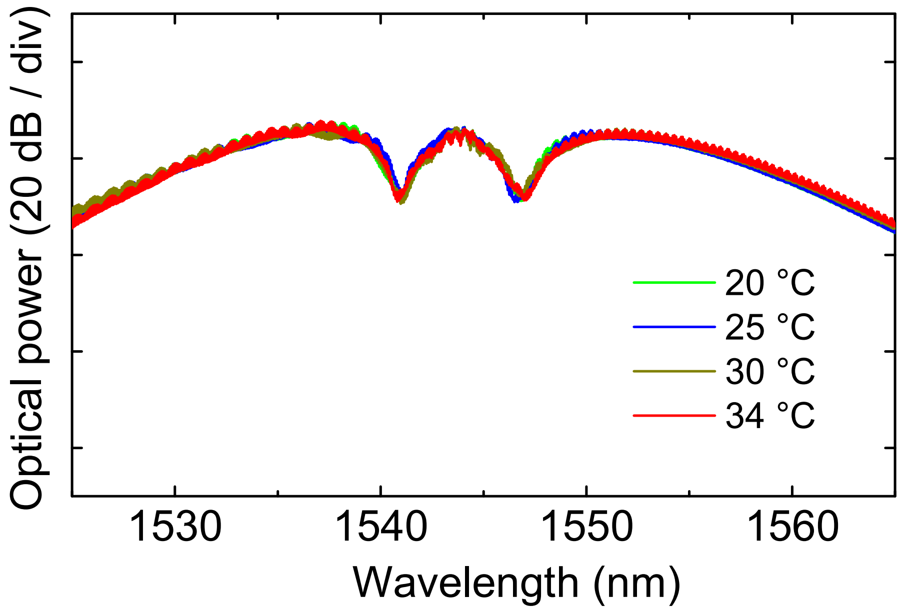


Fig. S6. Frequency comb broadening under different temperatures was measured at the output of the AlGaAs chip by an optical spectrum analyzer with a resolution bandwidth (RBW) of 0.1 nm.

7. Power consumption analysis of AlGaAs chip based frequency comb source compared to parallel WDM lasers

We investigated the power consumption of AlGaAs chip based frequency comb source and compared it with the power consumption of the state-of-the-art commercial parallel WDM lasers[2]. The power consumption of parallel WDM lasers is calculated by multiplying the power consumption per laser with the number of WDM channels. The power consumption of AlGaAs chip based frequency comb source is based on the configuration in Figure S7 with a target of 10 dBm per comb line. The pulses generated in the mode-locked laser are amplified by the EDFA 1 to ~20 dBm and then launched into the AlGaAs chip. The broadened frequency comb is amplified by the EDFA 2 to ~23 dBm and then amplitude equalized by a wavelength selective switch (WSS). The flattened frequency comb is amplified by the EDFA 3 and then split into individual comb lines by a wavelength demultiplexer for independent modulations. The output power of the EDFA 3 depends on the number of WDM carriers, e.g. in the case of 80 WDM channels the EDFA 3 output power is 29 dBm in order to achieve 10 dBm per line. The wall-plug power consumptions of the mode-locked laser (including driving electronics) and the controller (including locking electronics and temperature control) are measured, as shown in the Table S1. It is noted that the mode-locked laser used in the experiment is benchtop type research equipment, which consumes more power than the industrial implementation of the mode-locked laser. Therefore, the power consumption of the frequency comb source is actually overestimated and more energy saving is expected by using industrial implementation. The power consumptions of the EDFAs are estimated based on commercially available components[4, 5]. For the frequency comb source, the power consumption slightly increases with more WDM channels. However, the power consumption of the parallel WDM lasers scales linearly with the number of WDM channels. Therefore, more power can be saved for larger number of WDM channels by using AlGaAs chip based frequency comb source.

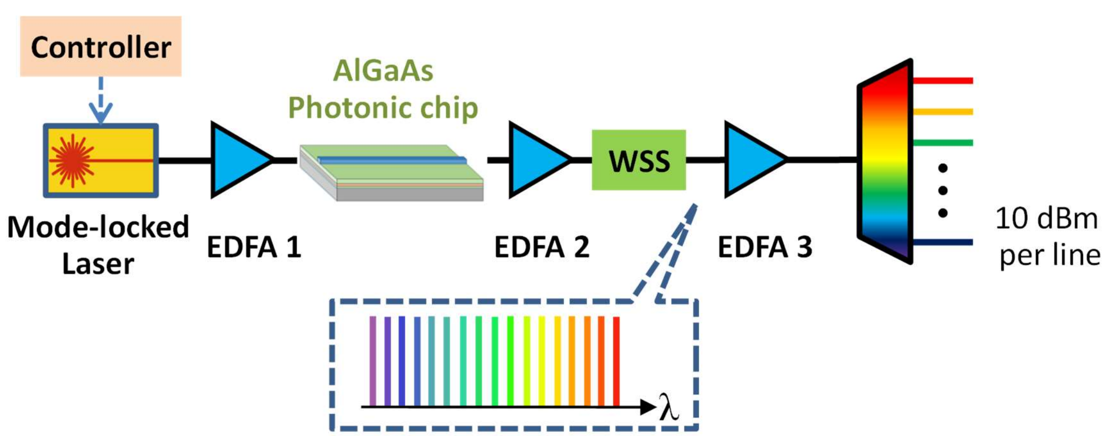


Fig. S7. Setup configuration for analyzing the power consumption of AlGaAs chip based frequency comb source with a target of 10 dBm per comb line.

Table S1. Power consumption for the frequency comb source and parallel WDM lasers with different number of WDM channels and targeting an optical power of 10 dBm per wavelength channel.

	Number of WDM channels	Power consumption (W)				
		Laser	Controller (including locking electronics)	EDFA 1 & EDFA 2	EDFA 3	Total power
Frequency comb source	80	19	19	8 + 11	18	75
	200	19	19	8 + 11	35	92
	400	19	19	8 + 11	45	102
Parallel WDM lasers	80	3.8 × 80	-	-	-	304
	200	3.8 × 200	-	-	-	760
	400	3.8 × 400	-	-	-	1520

8. Pump-to-comb conversion efficiency

The pump-to-comb conversion efficiency is defined as the ratio between the optical power in all the newly generated comb lines (excluding the remaining pump power) and the power of the initial pump[6-8]:

$$\eta_{\text{comb}} = \Sigma P_{\text{comb lines}} / P_{\text{pump}} \tag{5}$$

Figure S8A shows the schematic of the chip and the locations where the power should be measured in order to calculate the pump-to-comb conversion efficiency. Since the pump is coupled into the AlGaAs chip using a tapered fiber from one side and the broadened frequency comb is coupled out of the chip using another tapered fiber from the other side, there are coupling losses at both facets, α_{c1} and α_{c2}. These losses are not part of the frequency comb broadening itself, however, in practice the power can only be measured at the input and the output. The relations between the powers at different locations are shown below:

$$P_{\text{pump, remaining, out}} = P_{\text{pump, remaining}} \cdot \alpha_{c2} \quad (6)$$

$$\Sigma P_{\text{comb lines, out}} = \Sigma P_{\text{comb lines}} \cdot \alpha_{c2} \quad (7)$$

$$P_{\text{pump}} \cdot \alpha_{\text{wg}} = P_{\text{pump, remaining}} + \Sigma P_{\text{comb lines}} \quad (8)$$

In addition, there is also waveguide loss due to the scattering and absorption, α_{wg}. Therefore, the pump-to-comb conversion efficiency can be derived from the measured power and the waveguide loss:

$$\eta_{\text{comb}} = \alpha_{\text{wg}} \cdot \Sigma P_{\text{comb lines}} / (P_{\text{pump, remaining}} + \Sigma P_{\text{comb lines}}) \quad (9)$$

$$= \alpha_{\text{wg}} \cdot \Sigma P_{\text{comb lines, out}} / (P_{\text{pump, remaining, out}} + \Sigma P_{\text{comb lines, out}})$$

The broadened frequency comb at the output is shown in Figure S8B, consisting of three regions (Region I, Region II and Region III). The spectrum of the pump at the input is shown in Figure S8C. The pump has a 20-dB bandwidth of 6.3 nm (from 1539.8 nm to 1546.1 nm) and 99.6% total pump power is within the 20-dB bandwidth. The comb lines out of this wavelength range are considered as newly generated comb lines. Thus, the spectrum in the Region I (from 1520 nm to 1539.8 nm) and the Region III (1546.1 nm to 1570 nm) are considered as newly generated comb lines and the spectrum in the Region

II (from 1539.8 nm to 1546.1 nm) is considered as the remaining pump. The pump-to-comb conversion efficiency can be derived from the power of these three regions:

$$\eta_{comb} = \alpha_{wg} \cdot (\Sigma P_{\mathrm{Region\ I}} + \Sigma P_{\mathrm{Region\ III}}) / (\Sigma P_{\mathrm{Region\ I}} + \Sigma P_{\mathrm{Region\ II}} + \Sigma P_{\mathrm{Region\ III}}) \tag{10}$$

The propagation loss of the AlGaAs nano-waveguide is ~1.5 dB/cm and the waveguide loss of the 5-mm long nano-waveguide is ~0.75 dB, corresponding to the α_{wg} of ~0.84. Therefore, the pump-to-comb conversion efficiency (η_{comb}) is calculated to be ~66%.

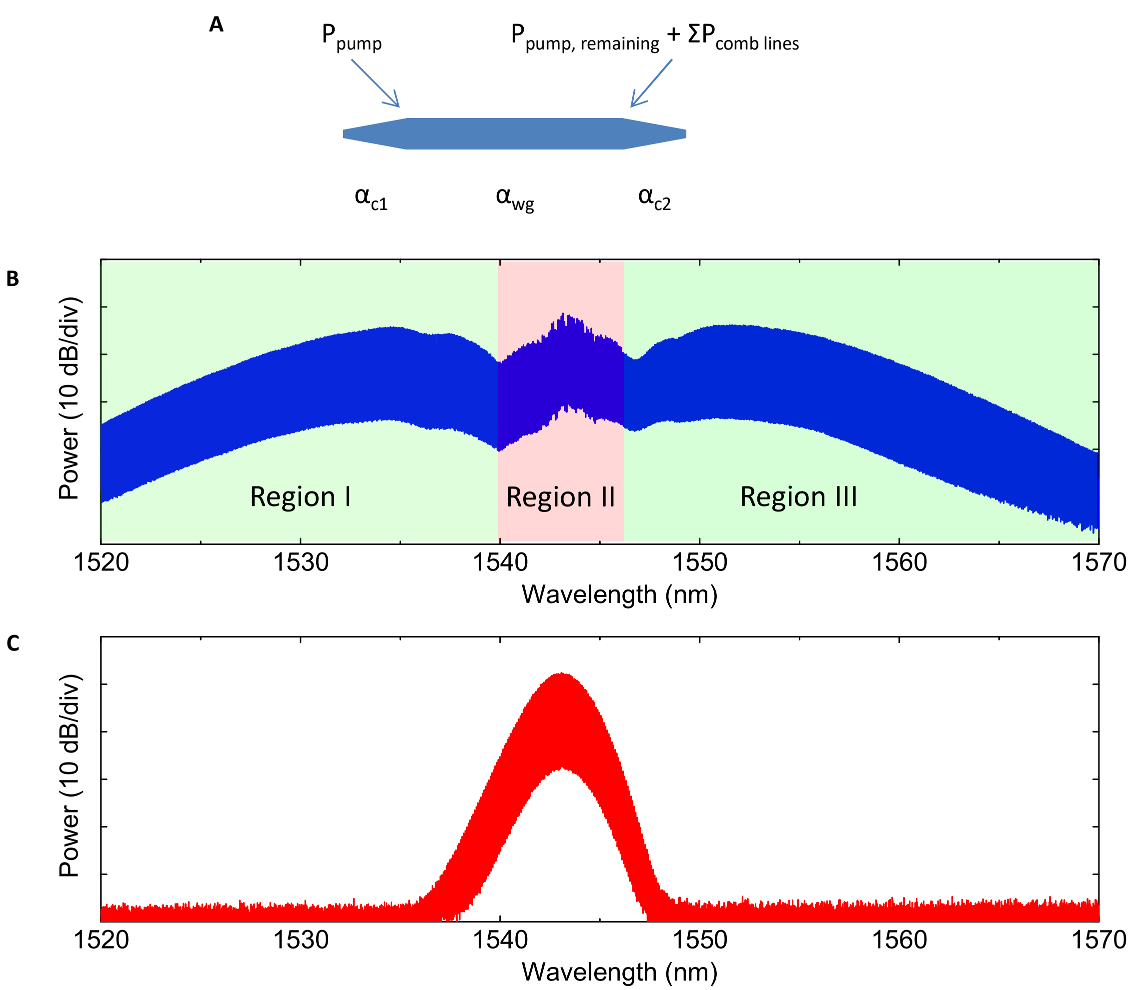


Fig. S8. **P**ump-to-comb conversion efficiency. A. Schematic of the chip and the locations where the power should be measured in order to calculate the pump-to-comb conversion efficiency. B. Spectrum of the broadened frequency comb consisting of three regions (Region I, Region II and Region III). The spectrum in the Region I (from 1520 nm to 1539.8 nm) and the Region III (1546.1 nm to 1570 nm) are considered as newly generated comb lines and the spectrum in the Region II (from 1539.8 nm to 1546.1 nm) is considered as the remaining pump. C. Spectrum of the pump at the input of the chip.

9. Frequency comb broadening in an AlGaAsOI nano-waveguide using 10 GHz picosecond and sub-picosecond pulses

Figure S9A shows the schematic drawing of the characterization setup for spectral broadening in an AlGaAsOI nano-waveguide using 10 GHz pulses. An erbium glass oscillator (ERGO) generates a 10 GHz pulse train at 1542 nm with a 1.5-ps pulsewidth. A polarization controller is used to align the polarization of the pump pulses to the transverse electric (TE) mode of the waveguide and an optical spectrum analyzer is used to record the output spectrum. The optical spectra at the input and the output of the AlGaAsOI nano-waveguide using 1.5-ps 10-GHz pulses are shown in Fig. 2 in the main manuscript, showing a comb easily covering the whole C-band.

To investigate the broadening further, the pump pulses are compressed to sub-picosecond widths to increase the peak power. After amplification in an erbium-doped fiber amplifier (EDFA), the pulses are launched into a dispersion flattened, highly nonlinear fiber (DF-HNLF) to compress the pulses to femtosecond pulses (FWHM of 230 fs), and then launched into an 11-mm long AlGaAsOI nano-waveguide (290-nm height and 500-nm width). Fig. S9B and S9C show the spectra at the input and the output of the waveguide with an average launched power of only 12 mW (peak power of 5.2 W). A broadened frequency comb with a 20-dB bandwidth of 153 nm (from 1460 nm to 1613 nm) is achieved, which covers S, C and L band.

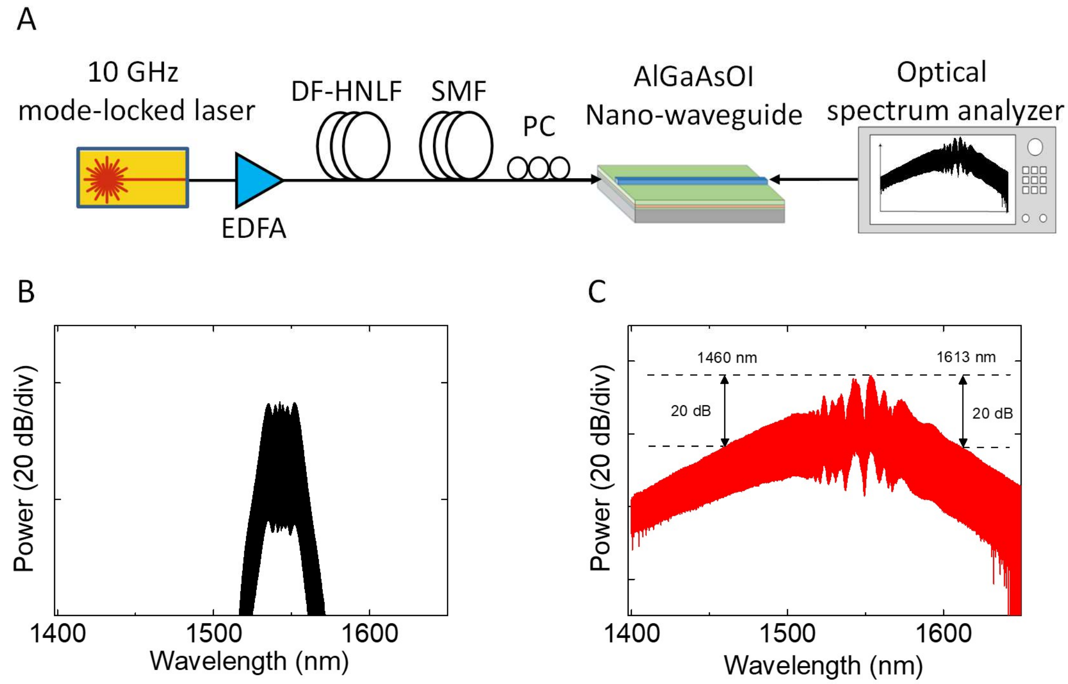


Fig. S9. Frequency comb broadening in AlGaAsOI nano-waveguide using 10 GHz sub-picosecond pulses. (A) Experimental setup. (B) and (C) Optical spectra before and after the Frequency comb broadening in AlGaAsOI nano-waveguide using 10 GHz sub-picosecond pulses.

10. Heterogeneous single-mode 30-core fiber with trench-assisted structure

In order to increase the capacity of optical transport systems employing multi-core fibers (MCFs), it is essential to increase the total number of cores in an MCF within a limited cladding area, which eventually results in a smaller core-to-core distance (or core pitch, Λ). The inter-core crosstalk (XT) in dB of MCFs is inversely proportional to the core pitch and the XT has to be under certain levels as high XT results in serious performance degradation in optical transmission systems. Thus, XT reduction methods have to be adopted in order to increase the number of cores in an MCF. Here, a refractive index trench-assisted structure was employed around each core to reduce the mode coupling between adjacent cores. In addition, by using four types of cores, neighboring cores have different refractive index profiles, which introduces phase mismatching between neighboring cores (Fig. S10), lowering XT.

Cores 1, 2, and 3 have a trench-assisted (TA) structure to reduce crosstalk, and core 4 is a step-index core with no trench cladding to avoid the lengthening of the cut-off wavelength of cores that are surrounded by TA-cores. The effective area (A_{eff}) of all cores was designed to be approximately 80 μm^2 although the effective indices, n_{eff}, are heterogeneous. The outer cladding thickness (T_c) was 33.8 μm to reduce excess loss due to a high-index coating. Average Λ was 29.7 μm, cladding diameter was 228 μm, and the fibre length L was 9.6 km.

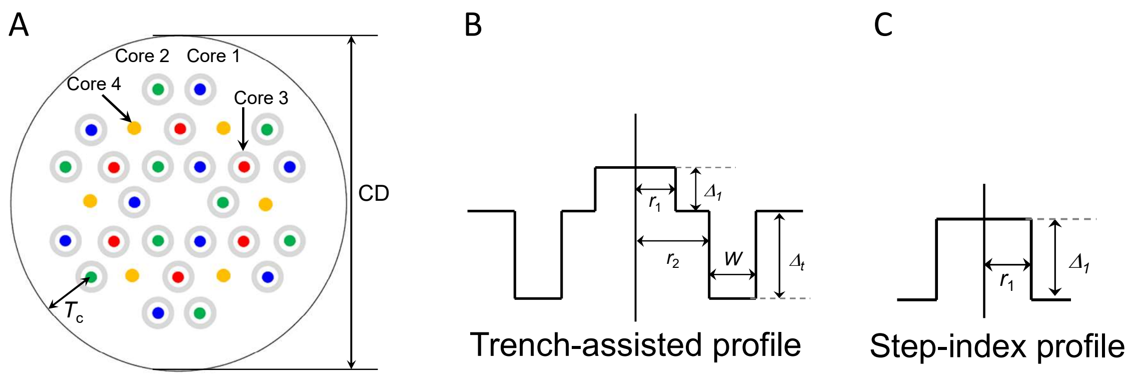


Fig. S10. Heterogeneous single-mode 30-core fiber with trench-assisted refractive index structure. (A): Schematic structure; (B) and (C): index profile (trench-assisted profile and step-index profile) of cores of the fabricated 30-core fiber.

11. Figure of merit for nonlinear platform

To compare the efficiency of various nonlinear platforms, a figure of merit (FOM) has been defined as the ratio between the maximal achievable nonlinear phase shift ($\emptyset_{max}$) and the medium length (L).

$$\mathrm{FOM} = \emptyset_{max}/L = \gamma P_{max} L_{eff}/L \tag{11}$$

where γ is the nonlinear parameter, P_{max} is the maximum input power and L_{eff} is the effective length of the nonlinear medium.

$$L_{eff} = (1 - \exp(-\alpha L))/\alpha \qquad (12)$$

α is attenuation coefficient and L is the length of the nonlinear medium. Therefore, the FOM can be written as:

$$\text{FOM} = \gamma P_{max}(1 - \exp(-\alpha L))/(\alpha L) \qquad (13)$$

Note that, for the α in the unit of dB/m, it is ≈4.343 times the power attenuationoefficient in 1/m. To calculate the peak power, the pulse duty cycle of 1.5% should be taken in account, since 10 GHz seed pulse with the pulewidth of 1.5 ps was used in the experiment.

The AlGaAsOI nano-waveguide has a nonlinear parameter (γ) of ~660 $W^{-1}m^{-1}$. The maximum average input power (P_{max}) for the current AlGaAsOI devices is ~100 mW limited by the fragile inversed tapers in the input coupling region, although the maximum input power can be optimized by using e.g. grating couplers. The attenuation of the AlGaAsOI nano-waveguide is 1.5 dB/cm. For the 5-mm long nano-waveguide, the calculated FOM is ~4000 m^{-1}.

A highly nonlinear fiber (HNLF) has a typical nonlinear parameter (γ) of ~10 $W^{-1}km^{-1}$.The maximum average input power (P_{max}) for the HNLF is ~2 W, limited by the fiber fuse effect[9]. The attenuation of a HNLF is typically 0.8 dB/km. For a HNLF with a typical length of 500 m, the calculated FOM is ~1.3 m^{-1}.

Therefore, the AlGaAsOI nano-waveguide has a FOM three orders of magnitude larger than that of a typical HNLF.

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