Broadband and repetition rate tunable frequency comb based on electro-optic time lens with AlGaAsOI waveguide

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Abstract *We present a tunable repetition rate frequency comb realized by cascaded electro-optical modulators with a high nonlinear AlGaAs-on-isolator waveguide. 18-26.5 GHz comb spacing tunability with broadband spectra was achieved. All the devices can be integrated onto a single chip, which makes this work useful for many applications.*

Introduction

The optical frequency comb (OFC) was developed decades ago. From its initial uses as a reference for the optical atomic clock, it has now become an indispensable device in optical communication, spectroscopy, optical computing, microwave photonics (MWP), optical arbitrary waveform generation, sensing, *etc*[1-4]. The OFC with adjustable tooth spacing has attracted wide attention, especially in MWP and optical communications. Although Kerr optical micro-combs and mode-locked fiber lasers are favored for their stable pulses with broad spectrum, their repetition rate is determined by the length of the cavity. Recent progress in changing the repetition rate in micro-combs has been demonstrated by controlling the temperature or the applied electric field[5][6], but the complexity of the system and the fine-tuning are still a challenge due to the step-like tuning range.

Electro-optic (EO) time-lens based frequency combs exhibit advantages in robustness and temperature insensitivity due to the non-resonant structure. Furthermore, it possesses the unique characteristics that the central wavelength and repetition rate tunability can be adjusted continuously and independently[7][8]. A chip-scale femtosecond pulse has been demonstrated by cascaded amplitude and phase modulators on an integrated lithium niobate photonic platform[9]. However, EO combs are hard to achieve broadband spectrum due to the weak EO interaction strength without complex structures. Supercontinuum generation (SCG) can be achieved by an EO comb cascaded with high nonlinear fibers (HNLF), which has been studied extensively with the development of fiber technology[10][11]. But this configuration is bulky because hundreds of meters of HNLF are required to achieve a significant spectral broadening. Although all fiber silicon core fiber parametric mixer for OFC generation has been reported recently[12], it still needs a high input power and the system is hard to integrate. Besides, none of the above methods displayed the tunability of the repetition rate of the OFC. III-V materials, mainly binary or ternary compounds made of Aluminum (Al), Gallium (Ga), Arsenic (As), and Phosphorus, have attracted more attention in photonics applications due to their high third-order nonlinearity[13][14], which is two to three orders of magnitude higher than SiO_2, Si_3N_4, and AlN[15][16]. In addition, two-photon absorption (TPA) in the telecom band can be effectively avoided by the band-gap management [17]. Therefore, these materials are more desirable to work as the spectral broadening medium for SCG.

Here, we first exhibit a tunable repetition rate, broadband frequency comb by introducing an EO comb with AlGaAs-on-isolator (AlGaAsOI) waveguide. 18-26.5 GHz comb spacing can be arbitrarily adjusted. Due to the high nonlinearity of the AlGaAsOI, our system achieves a 22 nm @-20 dB bandwidth containing 120 tones driven by a low input power. The whole system is quite simple and all the devices could be integrated onto a single chip in the future.

Methods and Results

Figure1 exhibits the schematic of broadband, repetition rate tunable OFC comb generation. A narrow-linewidth (<20kHz) continuous wave laser is used as the optical seed. A single phase modulator (PM) is sufficient to increase the number of comb teeth due to the high nonlinearity of AlGaAsOI. Hence, The EO comb can be achieved simply by cascading a dual-driven Mach-Zehnder intensity modulator (IM) and a PM. The IM and PM are driven by the same tunable RF oscillator. Intensity modulation ensures the pulse has a Gaussian shape, and the phase modulation induces a quadratic phase to the pulse, resulting in a periodic time lens with linear chirp[9][18][19]. In the time lens system, the pulse image in the time domain can match well with the spectral distribution in the frequency domain. Subsequently, the linearly chirp can be effectively compensated through the dispersive delay line (DDL) in order to reduce the pulse width since the self-phase modulation is proportional to the pulse peak power. Here, we used single mode fiber to act as the DDL, and 2.2 ps pulse duration can be achieved from the EO comb by optimizing group velocity dispersion (GVD) of DDL (5.5 ps/nm). After that, the input power is further increased by an EDFA before the pulse propagates into the high nonlinear AlGaAsOI to achieve the spectrum broadening.

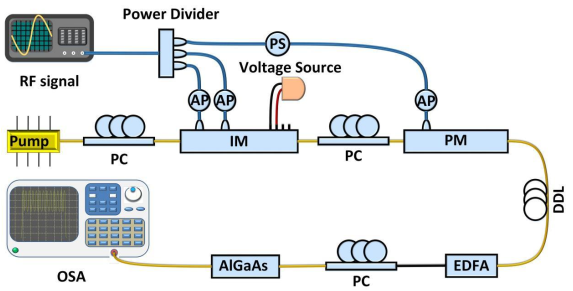

Fig. 1: A schematic of broadband, tunable repetition rate comb generated from EO-comb with AlGaAsOI waveguide. PC: polarization controller; IM: optical intensity modulator; PM: optical phase modulator; DDL: dispersive delay line; EDFA:Erbium-doped fiber amplifier; AP: amplifier; PS: phase shifter.

We used AlGaAsOI as the nonlinear optical waveguide (Fig. 2). A significant advantage of choosing AlGaAs as a nonlinear material over other semiconductors commonly used in integrated photonics is because of its relatively large band gap. Also, the bandgap of $Al_xGa_{1-x}As$ varies from 1.42 eV (872 nm) to 2.16 eV (574 nm)[20] by changing the Al mole fraction, which can be used to avoid TPA at the telecom band. In this work, x is selected as 0.2 to operate the comb at the C-band wavelength. Furthermore, AlGaAs has one of the highest nonlinear optical coefficient $n_2 = 2.6\times10^{-17}$ m^2W^{-1} when compared with other nonlinear materials.

The AlGaAsOI device is fabricated by wafer-scale heterogeneous integration technology by bonding a 400 nm AlGaAs onto a 4 inch Si wafer with 2 μm oxide on top. After substrate removal, the AlGaAs is patterned by DUV lithography and SiO_2 hardmask, followed by a PECVD cladding deposition. The simulated mode distribution of AlGaAsOI waveguide is plotted in Figure 2b. We calculated the dispersion curve under different widths when the thickness of AlGaAs was 400 nm, as shown in Figure 2c. Here, we use a width of 600 nm, and the calculated GVD is anomalous at the C-band wavelength.

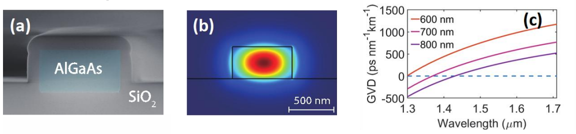

Fig. 2: AlGaAsOI nonlinear device. (a) An SEM image of the AlGaAsOI waveguide cross section. (b) Simulated intensity distribution of the waveguide fundamental TE mode for comb generation. (c) Simulated GVD of 400-nm-thick AlGaAsOI waveguides with different widths.

Sub-picosecond pulses achieved from the EO comb are amplified to 220 mW and launched into a 5-mm-long AlGaAsOI waveguide by lensed optical fiber (propagation loss of 0.3 dB cm^{-1}, insertion loss of 4 dB per facet). The spectrum rapidly broadened due to the high third-order nonlinearity of AlGaAs. Figure 3 shows the output spectrum before (red) and after (blue) the AlGaAsOI waveguide. The bandwidth is around 22 nm@-20dB, which is ten times broader than the spectrum bandwidth of the EO comb. The average output power of the broadened frequency comb is about 16 mW. This corresponds to an average power of 0.13 mW per comb line for ~120 comb lines within the telecom C-band.

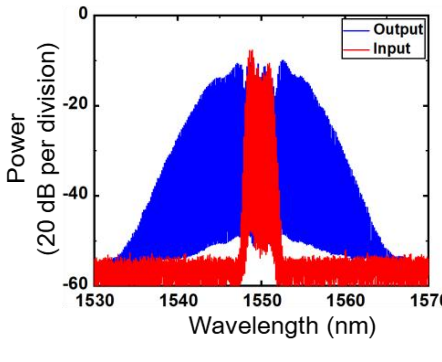

Fig. 3: Output spectrum from the EO comb (red) and AlGaAsOI waveguide (Blue).

A delayed self-heterodyne method was used to measure the linewidth of the broadened frequency comb. A tunable narrowband filter (EXFO-XTM-50, 0.1nm bandwidth) is used to choose one of the tones from the broadened frequency comb, and the selected tone is split into two branches by an optical coupler. One branch of the light is passed through a 35 km fiber delay for the elimination of coherence, and the other branch of the light is passed through an acoustic-optical modulator to shift the center frequency by 300 MHz. The beat note centered at 300 MHz was detected by an electrical spectrum analyzer. The measured electrical spectra are shown in Figure 4. Figure 4a and 4b exhibit the linewidth of broadened frequency comb at 1556.6 nm and 1544.1 nm, and the linewidth is 16 kHz @3dB and 15.2 kHz @3dB, respectively. The results proved that the linewidth of broadband OFC is almost equal to the seed source, indicating that the performance of the OFC is not degraded.

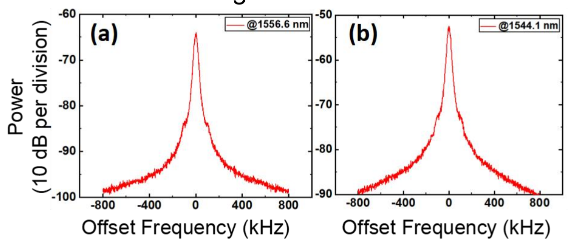

Fig. 4: Beat note at 1556.6 nm and 1544.1 nm for linewidth measurement of the broadened frequency comb.

Since the interval between each tooth matches the frequency of the RF source, the repetition rate of the source can be adjusted within the range allowed by IM and PM. In our system, RF frequency is limited by our amplifier and electronic devices. By setting the proper bias voltage and phase shift, 18-26.5 GHz spacing of the comb teeth can be tuned arbitrarily, as shown in Figure 5. A desirable spectral broadening can be achieved at different repetition rates and the broadening ratio is more than 7. To the best of our knowledge, this is the first demonstration of a tunable repetition rate OFC based on the EO modulator with nonlinear broadening.

Conclusions

In this paper, we demonstrate a high-performance frequency comb realized by cascaded EO modulators with AlGaAsOI waveguide. A repetition rate from 18-26.5 GHz can be arbitrarily tuned with a broad spectrum bandwidth and linewidth below 20 kHz. Since the system is simple and the discrete devices used here have already been demonstrated in silicon-based optoelectronic devices, it should be possible to integrate all the devices into one chip.

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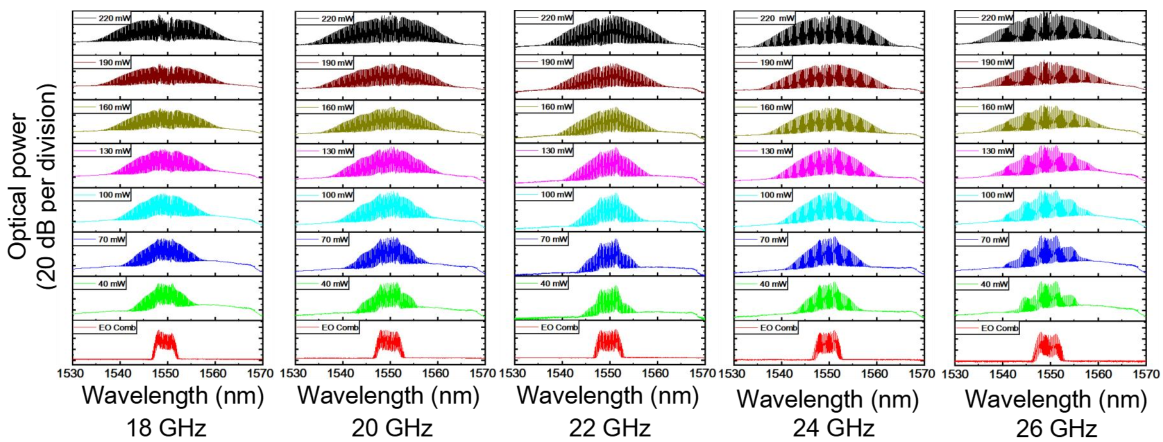

Fig. 5: Broadband frequency comb generation with different repetition rate.

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