Aluminum nitride as nonlinear optical material for on-chip frequency comb generation and frequency conversion

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Abstract: A number of dielectric materials have been employed for on-chip frequency comb generation. Silicon based dielectrics such as silicon dioxide (SiO$_2$) and silicon nitride (SiN) are particularly attractive comb materials due to their low optical loss and maturity in nanofabrication. They offer third-order Kerr nonlinearity ($\chi^{(3)}$), but little second-order Pockels ($\chi^{(2)}$) effect. Materials possessing both strong $\chi^{(2)}$ and $\chi^{(3)}$ are desired to enable self-referenced frequency combs and active control of comb generation. In this review, we introduce another CMOS-compatible comb material, aluminum nitride (AlN), which offers both second and third order nonlinearities. A review of the advantages of AlN as linear and nonlinear optical material will be provided, and fabrication techniques of low loss AlN waveguides from the visible to infrared (IR) region will be discussed. We will then show the frequency comb generation including IR, red, and green combs in high- $Q$ AlN micro-rings from single CW IR laser input via combination of Kerr and Pockels nonlinearity. Finally, the fast speed on-off switching of frequency comb using the Pockels effect of AlN will be shown, which further enriches the applications of the frequency comb.

1 Introduction

An optical frequency comb is a light source, which consists of equally spaced components in the frequency domain [1, 2]. Inherently, the comb is an accurate frequency ruler, thus it can be used as a standard in time—optical clocks [3–5]. The broad coherent spectrum of the comb enables other applications, such as remote sensing [6, 7], arbitrary optical waveforms [8], and wavelength calibration of astronomical spectrophotographs [9, 10]. Frequency comb generations by cascaded four-wave mixing (FWM) were first reported in SiO$_2$ micro-toroidal resonators [11–14]. The high-quality ($Q$) factor of the micro-resonator enhances the optical power in the micro-cavities, which reduces the threshold of the nonlinear processes and generates a frequency comb. In addition, crystalline materials such as magnesium fluoride (MgF$_2$) [15–17] and calcium fluoride (CaF$_2$) [18–20] have been demonstrated. However, these resonators are surrounded by the air and are mainly coupled with a tapered optical fiber, which is delicate and difficult to control the coupling gap precisely. Recently, robust and high resolution CMOS-compatible on-chip micro-ring resonators with various materials have been reported as other frequency comb sources. So far, SiN [21–25], high-index silica glass (Hydex) [26, 27], silicon (Si) [28], diamond [29], and aluminum nitride (AlN) [30–32] have been utilized based on their high-$Q$ and small footprint in SiO$_2$ cladding.

AlN has been used for second harmonic generation (SHG) and electro-optic devices based on its $\chi^{(2)}$ effect ($d_{33} = 1–3 \times 10^{-23} \mbox{C/V}^2$) [33–38]. Unlike SiN or SiO$_2$, AlN has both second ($\chi^{(2)}$) and third order ($\chi^{(3)}$) optical nonlinearities due to its non-centrosymmetric crystal structure. This property enables cascaded nonlinear effects including SHG, sum frequency generation (SFG), third harmonic generation (THG), four-wave sum frequency generation (FSFG) and FWM when high enough optical power is concentrated in a small volume. The micro-ring is a suitable resonator geometry for on-chip implementation, and these nonlinear phenomena are observed in AlN micro-ring [32]. Another advantage of AlN is the wide band gap (6.0–6.1 eV) [39, 40], which enables applications from ultraviolet (UV) to mid-infrared (IR) range [41, 42]. High thermal conductivity (319 W/mK) [43] and a small thermo-optic coefficient (2.7 $\times$ 10$^{-5}$ K$^{-1}$) [44] are also favorable factors considering heat dissipation in micro-rings, which becomes important for the nonlinear optical device to handle high power. Here, we review the unique frequency comb generation in the AlN micro-ring resonator and the utiliza-
tion of the strong Pockels nonlinearity of AlN for expanding the comb spectrum as well as for controlling the frequency comb.

2 Low loss AlN device fabrication

To observe strong nonlinear effects in AlN devices, the fabrication of a low loss and high-Q micro-ring is of crucial importance. We have optimized the fabrication process and have achieved optical Q of $10^6$ from AlN ring resonators. Fig. 1(a) shows the essential fabrication process steps. In this device, the 650-nm thick AlN is deposited on 2-μm thick thermally grown SiO$_2$ on Si substrate using an S-gun magnetron sputtering system [45]. The deposited film has around ±75 MPa stress and high c-axis orientation. The full width at half maximum of the X-ray diffraction rocking curve is typically less than 2°. From this AlN-on-insulator film, AlN waveguides are patterned using the E-beam lithography and reactive ion etching processes. Then through a plasma-enhanced chemical vapor deposition process, around 3-μm thick SiO$_2$ is used to cover and protect the entire chip. This cladding layer also leads to a more symmetric waveguide structure that further reduces radiation loss. Thermal annealing at 950°C for 10 hours is performed to increase the AlN and SiO$_2$ qualities. For fiber to chip butt coupling, both ends of the chip are cut and polished carefully. Fig. 1(b) is the transmission electron microscopy image of the fabricated AlN waveguide, which has c-axis oriented polycrystalline domains. The elements in this device, Si, Al, O, and N are shown from Fig. 1(c) to (f), respectively, by energy dispersive X-ray spectroscopy mapping.

AlN has a wide transmission window spanning from UV to mid-IR due to its large band gap [46]. Here, we show the test results of the optical transmission of AlN waveguides from visible to IR region. A single mode fiber with 4-μm mode field diameter (MFD) is employed for its better mode overlap with the waveguides. The typical coupling efficiency per facet is ~40% at 1550 nm. The other end of the 4-μm MFD fiber is spliced to a standard SMF-28 fiber, which is further used for all other fiber connections. By optimized splicing process, less than 0.2 dB splicing loss is realized. For testing in the IR regime, we use a tunable external cavity diode laser to measure the Q of micro-ring resonators with radii varied from 50 to 100 μm, heights from 800 nm to 1 μm, and widths from 3 to 4 μm. The high-Q factors near 1550 and 1950 nm wavelengths correspond to optical losses of 0.4 dB/cm and 0.3 dB/cm, respectively (Fig. 2(a), (b)). The transmission in visible regimes is tested.
using 520 and 635 nm wavelength laser diodes (Fig. 2(c), (d)). As these sources are not tunable, we fabricate long spiral waveguides (~1 cm) and record the scattered light using a CCD camera. Propagation losses are estimated to be 13 ± 3 dB/cm and 3 ± 1 dB/cm at 520 and 635 nm, respectively. The optical transmission, especially in the visible region, are significantly improved after the optimized annealing, indicating that the optical loss can be further reduced by material improvement.

3 Frequency comb generation in AlN micro-ring

In high-Q AlN micro-ring resonators, cascaded FWM takes place at high circulating optical power. First, phase-matched signal and idler are generated from the optical pump via degenerate FWM (2\(\omega_p = \omega_I + \omega_S\)). The resulting signal and idler frequency components undergo resonant enhancement and couple with pump to produce additional frequency lines through a non-degenerate FWM (\(\omega_p + \omega_S = \omega_I + \omega_{S1}\)) process. Through this cascaded FWM, more frequency components can be generated and finally, a frequency comb is obtained [11]. The top-left inset in Fig. 3 shows the energy diagrams of the cascaded FWM. However, the resonances of the micro-ring and comb peaks have different spacing due to the dispersion, which eventually limits the comb bandwidth (Fig. 3).

We minimize the dispersion of the AlN waveguides by controlling the waveguide width to achieve a frequency comb with a bandwidth of 250 nm in wavelength. The top-right inset in Fig. 3 is the microscope image of the 60-\(\mu\)m radius AlN micro-ring used in this experiment.

To obtain near-zero dispersion, we set the waveguide width to be 3.5 \(\mu\)m, which supports multiple modes near 1550 nm wavelength. As a result, many other modes with different FSRs, \(Q\) factors, and extinction ratios are observed. In a micro-ring resonator with 500 nm coupling gap, the three TE modes, the fundamental (red), the second order (blue), and the third order (magenta) modes are observed when the input polarization is adjusted to TE mode (Fig. 4). Their FSRs are 370, 361, and 348 GHz, respectively, indicating that higher order modes have higher group indices. The inset shows a fundamental TE mode resonance with loaded \(Q\) of ~500,000.

Fig. 5 shows the sequence of frequency comb generation in the micro-ring resonator. A 2 W input pump is generated from a tunable continuous wave (CW) diode laser followed by an erbium-doped fiber amplifier (EDFA). We slowly scan the input wavelength from shorter to longer wavelength, typically around 3 nm, near the fundamental TE mode resonances, and begin to observe the FWM peaks when the circulating power in the micro-ring reaches the threshold power [Fig. 5(a)]. Upon further tuning the pump to a longer wavelength (~0.1 nm), more power circulates in the ring and leads to more FWM peaks as shown in Fig. 5(b). When the pump is tuned deeply (~0.1 nm) into the resonance, the frequency comb evolves to a repetition rate of one FSR [Fig. 5(c)]. The threshold power is approximately 210 mW in the waveguide, and the AlN Kerr coefficient is estimated to be \(n^2 = 2.3 \pm 1.5 \times 10^{-15}\) cm²/W [30].

Our waveguide design is optimized for TE fundamental mode based on finite element method simulations. Fig. 6 shows the numerically calculated group velocity
dispersion for fundamental TE and TM modes of the AlN waveguide of 650 nm by 3.5 µm. The fundamental TE mode (black curve) has near zero anomalous dispersion, but the fundamental TM mode (red curve) has higher anomalous dispersion at 1550 nm wavelength. Still, we observe frequency combs from both TE and TM modes, as the AlN ring resonators have high enough Qs in both modes. The red and black comb spectra are from TM and TE polarization input pumps, respectively. Their mode power profiles and the directions of electric fields (black arrows) are shown in the insets close to the spectra. The bandwidth of TM mode comb (~70 nm) is shorter than the TE mode comb (~250 nm) due to higher dispersion of TM mode at 1550 nm wavelength.

4 Multi-comb generation from green to IR region

The frequency comb from FWM is not the only nonlinear phenomenon we can observe from the AlN micro-ring. Additional nonlinear effects such as SHG, THG, and SFG from the comb lines are detected due to the strong $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities of AlN. Fig. 7 illustrates the principle of multi-comb generation through FWM and SFG. In a high-Q micro-ring resonator, a Kerr frequency comb near the pump frequency is generated through the cascaded FWM [Fig. 7(a)] and generally expressed by $f_1 = f_o + nf_r$, where $f_o$ is the offset frequency, $f_r$ is the comb repetition rate, and $n$ is an integer. It also can be expressed by $f_1 = f_P + mf_r$, where the $f_P$ is the pump frequency and $m$ is an integer. The energy diagram shows a general case. It starts from degenerate FWM ($a = b = 0$), and then all combinations are possible if $a + b = c + d$ is satisfied within the comb bandwidth, where $a, b, c, d$ are integers. These comb lines near the pump combine together and generate additional frequency combs near the doubled and tripled pump frequencies. Through the Pockels effect, SHG and SFG among the comb lines are enabled and create frequency lines around the doubled pump frequency, $2f_p$ [Fig. 7(b)]. The red lines are from SHG and the blue lines are from the SFG of the initial comb lines. By combination of these two processes, a double frequency comb with the same $f_r$ as the initial comb is possible, and they can be expressed by $f_2 = 2f_P + mf_r$. Similar to this comb doubling, frequency comb lines at the triple of pump frequency are also generated by THG and FSFG, and expressed by $f_3 = 3f_P + mf_r$ [Fig. 7(c)]. Here, the $3f_r$-repetition rate comb lines are from THG (red lines) only, and FSFG fill the gaps (blue lines) and complete the $f_r$-repetition rate comb around the tripled pump frequency, $3f_P$. In the energy diagram of SFG and FSFG, $a + b = c$ and $a + b + c = d$ should be satisfied. By this combination of second ($\chi^{(2)}$) and third order ($\chi^{(3)}$) optical
nonlinear effects, multi-combs from the visible to the IR region are generated.

Figure 7: Schematics of multicomb generation with the same repetition rate \( f_j \) from the combination of various nonlinear effects: FWM, SFG and FSFG. (a) The initial IR comb generation from cascaded FWM. (b) The second comb near the doubled frequency, \( 2f_p \), arising from SHG and SFG of the initial comb. (c) The third comb near the tripled frequency, \( 3f_p \), generated from SHG and SFG of the initial comb. FWM: four-wave mixing; SFG: sum frequency generation; FSFG: four-wave sum frequency generation; SHG: second harmonic generation; THG: third harmonic generation.

For efficient wavelength conversion, the energy and momentum conservation (insets in Fig. 8) should be satisfied. As the frequencies are already fixed in the energy conservation equation, the refractive index of the new frequency \( n_3 \) in (a) and \( n_a \) in (b) should be between the indices of the pump frequencies. To find the solutions, the effective indices for the waveguide of 650 nm by 3.5 μm, which is the cross section of the micro-ring, are simulated in Fig. 8. The black solid line is for the fundamental TE mode near 1550 nm wavelength, and the red and green lines are for all TE modes near 775 and 520 nm wavelengths, respectively. In this wavelength range, two modes near 775 nm and 11 modes near 520 nm cross the black solid line, where the phase-matching conditions are satisfied. The corresponding mode overlap values are 0.047 and 0.007 for conversion to the red, and between 0.0035 and 0.44 for conversion to the green. The mode overlap is defined as:

\[
\xi = \frac{2\pi R}{\left[ \left( \frac{\omega_a}{\varepsilon_a \omega} \right)^2 + \left( \frac{\omega_b}{\varepsilon_b \omega} \right)^2 \right]^{1/2}} \int V_{\text{Waveguide}} dx dy (u_{a,x} \ast u_{b,x}),
\]

where \( R \) is the micro-ring radius, \( \omega_a, \varepsilon_a \) \( \omega_b \) and \( \varepsilon_b \) are the fundamental frequency, its permittivity, SHG (THG) frequency and permittivity at SHG (THG), respectively. \( V \) is the mode volume, and \( n \) is 2 for SHG and 3 for THG. \( u_{a,x} \) and \( u_{b,x} \) are the electric field along \( x \) direction for TE fundamental and SHG (THG) wavelength.

In the case of ring resonators, the lines are not continuous, as the resonant modes are discrete. This mismatch can be compensated by the thermal tuning of resonant wavelengths as the power in the micro-ring is increased. Additionally, the visible resonances have wide bandwidth (lower Q), which provides reasonable margin for phase matching. Especially in SFG from comb peaks, the best phase-matched combination among the IR comb peaks can be chosen for signal and pump. Although the phase matching is not perfectly satisfied, the high circulating power in the ring makes the wavelength conversion measurable in our experiment.

Figure 9 shows simplified schematics of multi-frequency comb generation and measurement setup. CW laser near 1550 nm wavelength is used in conjunction with EDFA and fiber polarization controller to create a 2 W TE input pump. In the micro-ring, frequency combs are generated near IR, red, and green region through combination of the nonlinear effects explained above. When the visible comb is generated, red and green scattered lights from the micro-ring are observed through an upright microscope as shown in Fig. 9. The visible combs in the micro-ring are also coupled out to an output single mode fiber, and 1% of collected power is used to assist fiber to chip alignment and IR comb spectrum measurement. The remaining output power is sent to the CHIRON spectrometer for precision comb spectrum analysis in the visible regime [47, 48]. In the spectrometer, an Echelle grating and a prism are used to produce a two-dimensional spectrum in visible range from 410 to 880 nm wavelength with a total of 73 rows. Each row covers from 4 nm (at 410 nm) to 13 nm (at 880 nm) wavelength span due to the inherent dispersion of the spectrometer.

Fig. 10 is a portion of CCD image obtained from the visible spectrometer that shows the visible combs near 776 and 517 nm wavelengths when the pump wavelength is tuned to 1552 nm resonance. This two-dimensional spectrum has zigzag wavelength direction as indicated at the top right of this figure. A total of 84 peaks are counted.
Figure 9: The simplified experimental set-up for multi-comb generation and spectrum measurement. The insets show optical microscope images of visible microcombs glowing red and green after using a chromatic filter for each wavelength (775 nm and 517 nm, respectively). CW: continuous wave, EDFA: erbium-doped fiber amplifier, FPC: fiber polarization controller, PD: photo detector, OSA: optical spectrum analyzer.

Figure 10: Selected portion of visible spectra recorded from the CCD camera and zoomed-in images near 776 nm and 517 nm spectral regions. The direction of the wavelength is shown in top right of the figure. The white dotted lines represent the boundary between different grating orders. Both visible combs have repetition rates of 369 GHz, which is the same as the initial IR comb repetition rate. IR: infrared.

near the 776 nm wavelength, which is the SHG peak from the IR pump wavelength, 1552 nm. Near the 517.3 nm wavelength, which is the THG peak from the IR pump, 43 comb peaks are detected. In the zoomed-in images of 776 and 517 nm spectral regions, white dotted lines divide the different grating orders. Within each grating order, all the spots have identical spacing of 369.2 ± 0.2 GHz, which is the same with the frequency repetition rate ($f_r$) of the initial IR comb. Red, green, and IR combs having the same repetition rate are due to the combination of different nonlinear effects in the AlN micro-ring as explained in Fig. 7. As each comb peak power is less than 100 pW, except the SHG peak (~1.2 nW), we expose the detector for 20 minutes to compensate for the low power. This low conversion efficiency can be improved by adding a separate drop-port coupling waveguide and optimizing the phase-matching condition for specific wavelength [49]. Some peaks are indexed accordingly to track their offsets from the SHG of the pump, as shown in Fig. 11.

Figure 11: A portion of IR comb spectra (top) and the corresponding visible comb spectra extracted from Fig. 10 (bottom). (a) Red comb generation from SHG and SFG. (b) Green comb generation from THG and FSFG. IR: infrared; SHG: second harmonic generation; SFG: sum frequency generation; THG: third harmonic generation; FSFG: four-wave sum frequency generation.

Fig. 11 shows a section of the spectra measured by the IR optical spectrum analyzer (OSA) (top, black), and the corresponding visible spectra extracted from Fig. 10 (bottom, colored). Fig. 11(a) demonstrates five red peaks near the 775 nm wavelength that are generated from the three comb lines in IR region. The red peaks labeled as “0”, “−2”, and “−4” are generated by both SHG and SFG, whereas the peaks “−1” and “−3” are only from SFG of IR peaks. Fig. 11(b) shows how the green comb lines are generated from the IR comb through THG and FSFG. Since the third order nonlinear process (THG or FSFG) has one more frequency component than the second order nonlinear process (SHG or SFG), only two IR comb lines are necessary to produce four green comb lines. The green peaks labeled as “0” and “−3” are mainly from THG of IR peaks, while the peaks “−1” and “−2” are from FSFG of IR peaks. For example, a photon corresponding to “−2” peak can be generated by the combination of two 1549 nm photons and one 1552 nm wavelength photon.

5 Fast comb switching in the AlN micro-ring

The second order nonlinearity also makes the fast comb on-off switching possible. By applying an electric field to the AlN micro-ring, the resonant condition is controlled
Figure 12: (a) The top view of fabricated device for fast comb on/off switching. (b) The simulated result of the electric field (red arrows) and electric potential (color map) at the AlN waveguide. (c) Experimental result of the resonance shift when DC voltage is applied to the electrode from −100 to 100 V. AlN: aluminum nitride.

Figure 13: Experimental set-up for frequency comb generation and switching. Power at PD is a filtered comb line, which is an indication of the comb on / off switching. PG: pulse generator, BPF: band pass filter. PD: photo detector.

Figure 14: (a) The applied control voltage and the recorded comb line power variation. Inset illustrates the selected comb line after an optical band pass filter. A thermal effect is observed from off to on state. (b) The optical transmission of micro-ring resonator due to the applied modulation voltage in linear region for comparison. The thermal effect is also observed after the fast electro-optic switching.

from the electro-optic Pockels effect [33]. This adjusts the optical circulating power in the micro-ring and leads to on-off switching of the frequency comb. Fig. 12(a) shows a top view of an array of microcomb devices with control electrodes. The simulated electric potential and field are shown in Fig. 12(b). The electric field at the AlN waveguide is around 50 kV/m when 1 V is applied between the top electrode and the bottom of the Si substrate. By applying DC voltage from −100 to 100 V to the gold electrodes of the fabricated device, the linear resonant peak shift (0.18 pm/V) is observed without decreasing the optical Q [Fig. 12(c)].

The experimental set-up for comb switching is shown in Fig. 13. First, the frequency comb is generated in the micro-ring and measured using the OSA with 1% of the output light. The 99% of the output power is sent to a tunable band-pass filter (BPF) that passes only one of the comb lines. The power of the selected comb line is recorded with a photo detector (PD) in time domain that indicates the on-off states of the comb. A pulse generator is used for high-speed modulation, and its signal is also recorded in time domain to compare with the signal from the PD using a computer.

Fig. 14(a) shows the applied voltage (blue) and the corresponding comb line power variation (red) in the time domain. The inset explains that the measured signal is from one comb line after BPF. The default setting in here is “comb on” when there is no applied voltage. When 40 V is applied to the device with the fixed pump, the comb line power becomes 0 in approximately 10 ns, which indicates the “comb off” state, resulting from the resonance shift due to the electro-optic effect. The comb line power is restored when the applied voltage is removed after an overshoot. The following transient decay is due to thermal relaxation after reduction of the circulating power within the micro-ring. This thermo-optic effect is also observed in the linear region without the optical nonlinear effect. Fig. 14(b) shows the applied voltage of 40 V (blue) and the transmission power measurement with the fixed pump near resonance (red). The sharp optical power change is due to the fast electro-optic effect, and the following transient decay is due to the slow thermal effect. It can be seen that even with including the slow thermal effect, fast on-off comb switching less than 1 µs is demonstrated.

6 Conclusion

In this review, we demonstrate optical frequency comb generation in an AlN micro-ring and its applications from
the second and third order nonlinearities of AlN. The optimized fabrication process and unique properties of AlN enable multiple nonlinear effects over a wide wavelength range in high-Q waveguide cavities. Multiband combs with identical repetition rate are generated near green, red, and IR regions from the cascaded FWM, SFG, and FSFG in the AlN micro-ring. The phase-matched AlN micro-ring can also be used to double an input fiber comb through a combination of SHG and SFG processes. In addition, the fast comb on-off switching using the Pockels effect of AlN is shown. Such novel nonlinear optical phenomena are enabled by a unique combination of second and third order nonlinearities possessed by the AlN material.

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