High-Speed Data Transmission via Wafer-Scale Aluminium Nitride Microresonator Frequency Comb

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ABSTRACT

The rapid advancement of photonics is driven by growing need for high-capacity transmission in AI and data-center interconnects. Silicon photonics enables low-cost CMOS fabrication, but conventional materials lack second-order nonlinearity and rely on laser-diode arrays for multi-channel links, increasing cost and complexity. A frequency comb provides a single multi-wavelength source that simplifies the system. Meanwhile, aluminum nitride (AlN) is a CMOS-compatible material with wide transparency and significant second-order nonlinearity. Here, we demonstrate high-speed transmission using a frequency comb generated from a high-Q ($>1\times10^6$) AlN microring on an 8-inch CMOS-compatible platform. A pump laser is amplified, coupled into the resonator to generate comb, and a selected comb line is filtered, re-amplified, and intensity modulated. Using a Mach–Zehnder modulator, we transmit 29-GBaud PAM4 and 30-Gbps NRZ signals over 10 km of fiber. The obtained BERs of 10^{-8} (PAM4) and 10^{-6} (NRZ) surpasses typical FEC limits. Open eye diagrams have high similarity to back-to-back results, demonstrating strong potential of AlN-based combs for scalable cost-effective high-speed communication.
Keywords: Integrated optics devices; Integrated optics materials.

INTRODUCTION

The rapid advancement of photonics technology has been driven by the fast-growing demand for high-capacity data transmission. High-speed, low-power, and low-cost data links are required for modern applications such as tele-medicine, interactive video, and cloud computing. Such demand has been further increased by the rise of artificial intelligence (AI) and large-scale data centers [1–3]. Silicon photonics technology provides a cost-effective solution, as it leverages existing Complementary Metal-Oxide-Semiconductor (CMOS) fabrication facilities [4–10]. A coherent light source is a key building block in silicon photonics platform. Conventional high-speed data transmission systems rely on arrays of laser diodes, which add cost, complexity, and power consumption [11–14]. An integrated optical frequency comb, in contrast, is a single multi-wavelength light source that can greatly simplify system and reduce overall cost [15–21]. However, traditional photonics materials used in silicon photonics platforms have inherent limitations, such as an indirect bandgap and the absence of second-order nonlinear effects (e.g., the Pockels effect) [22]. As an emerging photonics material, aluminum nitride (AlN) has gained a lot of interest due to its wide transparency window, second-order nonlinearity, and compatibility with CMOS fabrication processes [23–27].

In this work, we demonstrate high-speed data transmission using an integrated optical frequency comb light source generated from a high-Q AlN microring resonator. The comb source is fabricated on our CMOS-compatible 8-inch AlN photonics platform, where the microring resonator exhibits an intrinsic Q of $> 1\times10^6$, enabling generation of multiple comb lines. A continuous-wave pump laser is amplified through Erbium-doped fiber amplifier (EDFA) and coupled into the microring resonator to generate the comb lines. The first sideband comb line is extracted using a bandpass filter, re-amplified, and filtered again to suppress EDFA noise before intensity modulation.

For transmission tests, the selected comb line is then modulated using a Mach–Zehnder modulator (MZM) with either 29-GBaud PAM4 or 30-Gbps NRZ signals. The modulated signal is transmitted through 10 km of standard single-mode fiber, emulating inter-data-center communication. A back-to-back (B2B) configuration using a tunable laser with equivalent power level is used for reference. Bit-error-rate (BER) and eye diagrams are measured using a high-speed photoreceiver and Bit-error-rate tester (BERT).

The AlN-comb-based intensity modulated direct detection (IMDD) transmission achieves BER as low as 10^{-8} for 29-GBaud PAM4 and 10^{-6} for 30-Gbps NRZ after 10 km, which far surpassing most forward error correction (FEC) limits. Eye diagrams for both formats remain open after fiber transmission, showing high similarity compared with B2B. The PAM4 eye shows slight closure due to the EDFA noise not being completely removed by the bandpass filter. The NRZ eye exhibits a jitter of ~4.1 ps, which is comparable to the B2B of 4.08 ps. The results confirm the cost-effectiveness of AlN-based frequency combs as multi-wavelength sources for high-speed optical communication, demonstrating the strong potential of the AlN photonics platform for scalable data-transmission systems.

ALUMINUM NITRIDE DEVICE DESIGN AND PREPARATION

The frequency-comb generator is based on a high-Q microring resonator with a design similar to that reported in our previous work in Ref. [28] and is fabricated on the same CMOS-compatible platform described in Refs.[29,30]. A schematic of the device is shown in Fig. 1(a). For this batch of devices, an AlN thin film with a thickness of 739 nm is deposited on a thermally grown SiO_2 layer on a silicon substrate at the wafer scale using a sputtering process, which is widely adopted in CMOS foundries for thin-film deposition [31–34]. Subsequent lithography and dry etching processes are fully CMOS-compatible and performed uniformly across the 8-inch wafer. A photo image of the fabricated wafer is shown in Fig. 1(b).

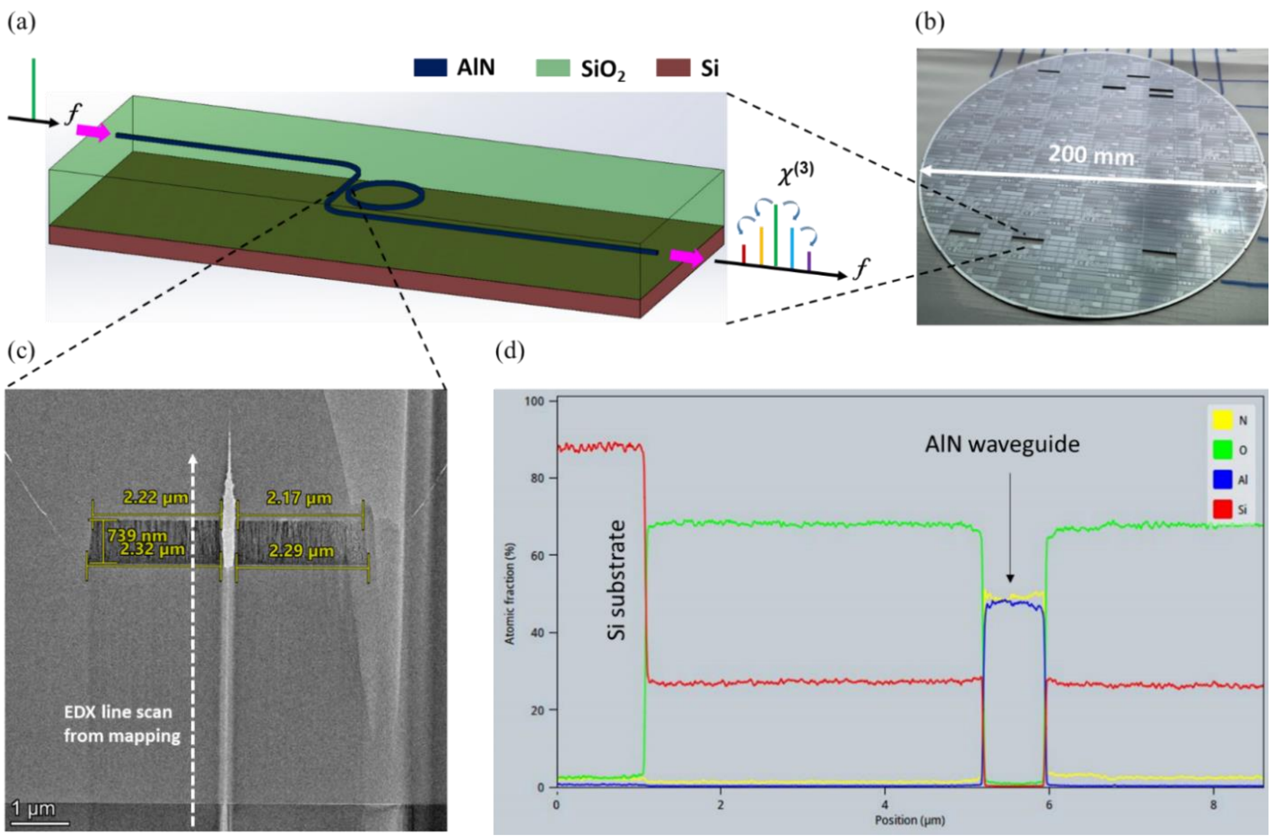

Figure 1. (a) Schematic of the AlN microring resonator used for frequency comb generation. (b) Photograph of the fabricated 8-inch wafer with AlN photonic integrated circuits patterned using a CMOS-compatible process. (c) Cross-sectional FIB-SEM image of the coupling region between the bus waveguide and the microring resonator. (d) Atomic fraction profiles extracted from the EDX line scan indicated in (c), confirming the stoichiometric composition of the AlN waveguide and the absence of elemental contamination.

The microring resonator is formed by an AlN waveguide with a nominal width of ~2.2 µm and a bending radius of 160 µm. The coupling gap between the bus waveguide and the microring is designed to be 0.5 µm. A cross-sectional view of the coupling region is obtained using focused-ion-beam scanning electron microscopy (FIB-SEM), as shown in Fig. 1(c). Notably, a small air gap is observed between the two waveguides due to the non-conformal nature of the top oxide cladding.

To verify the material quality and compositional uniformity of the AlN waveguide, energy-dispersive X-ray spectroscopy (EDX) is performed along the dotted white line indicated in Fig. 1(c). The corresponding atomic fraction profiles, plotted in Fig. 1(d), confirm the stoichiometric composition of the AlN film and the absence of detectable contamination from other elements. These results validate the suitability of the wafer-scale CMOS-compatible AlN platform for high-Q nonlinear photonic devices.

HIGH-SPEED DATA TRANSMISSION

High-speed data transmission experiments are conducted using the setup illustrated in Fig. 2(a). A frequency comb is generated by sweeping an amplified continuous-wave laser from the blue side into a resonance of the AlN microring. Optical amplification is provided by an L-band EDFA to reach the threshold for comb generation. The optical spectrum measured at point A in Fig. 2(a) is shown in Fig. 2(b).

The first sideband of the generated frequency comb at 1565.92 nm is selected using a bandpass filter (BPF1), subsequently amplified by a second EDFA (EDFA2), and filtered again using BPF2 to suppress amplified spontaneous emission (ASE) noise. The filtered comb line is then modulated by a MZM with either 29-GBaud PAM4 or 30-Gbps NRZ electrical signals. The modulated optical signal is transmitted through 10 km of standard single-mode fiber (SMF), emulating inter-data-center transmission links, and finally detected by a high-speed photoreceiver. BER and eye-diagram measurements are performed using a BERT and a digital sampling oscilloscope (DSO), respectively.

For comparison, B2B measurements are carried out using a tunable laser with equivalent optical power and a linewidth of 100 kHz at point A in Fig. 2(a). As shown in Fig. 2(c), the 30-Gbps NRZ transmission exhibits a negligible power penalty (~0.15 dB) compared to the B2B reference, while the 29-GBaud PAM4 transmission achieves a minimum BER of 10^{-8}. The corresponding NRZ and PAM4 eye diagrams after 10 km transmission remain well open and closely resemble the B2B results, as shown in Fig. 2(d)–(g).

The measured BER values of 10^{-8} for PAM4 and 10^{-6} for NRZ transmission after 10 km fiber are well below typical FEC thresholds, demonstrating the suitability of the AlN-based frequency comb for IMDD systems. The slight eye-closure observed in the PAM4 transmission is mainly attributed to residual ASE noise from EDFA2, which is not fully suppressed by the optical filtering stages. Overall, these results confirm the strong potential of wafer-scale AlN microring frequency combs as cost-effective, multi-wavelength light sources for scalable high-speed optical communication systems.

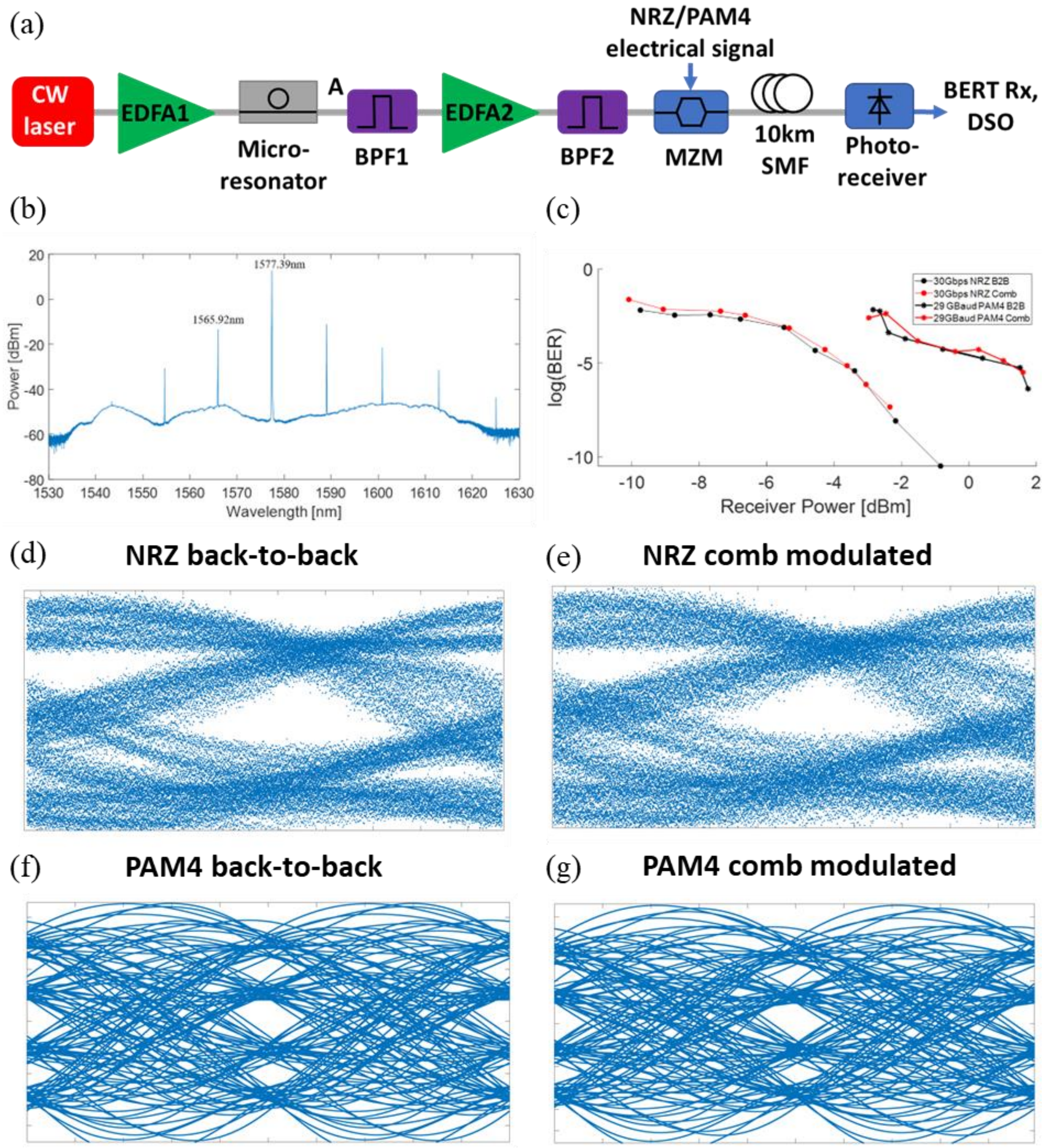

Figure 2 (a) Experimental setup for high-speed data transmission using an AlN microring-based frequency comb. EDFA: erbium-doped fiber amplifier; BPF: bandpass filter; MZM: Mach–Zehnder modulator; NRZ: non-return-to-zero; PAM4: pulse-amplitude modulation with four levels; SMF: single-mode fiber; BERT: bit-error-rate tester; DSO: digital sampling oscilloscope. (b) Optical spectrum of the generated frequency comb measured at point A in (a). (c) Measured BER performance of comb-modulated transmission (red) compared with back-to-back reference (black) for both 30-Gbps NRZ and 29-GBaud PAM4 signals. (d,e) Eye diagrams for NRZ transmission in back-to-back and comb-modulated configurations. (f,g) Eye diagrams for PAM4 transmission in back-to-back and comb-modulated configurations.

CONCLUSION

In conclusion, we have demonstrated high-speed optical data transmission enabled by an integrated optical frequency comb generated from a high-Q AlN microring resonator fabricated on a CMOS-compatible 8-inch platform. The AlN microring exhibits an intrinsic quality factor exceeding 1×10^6, enabling the generation of stable multi-wavelength comb lines under continuous-wave pumping. By selecting and modulating a single comb line, IMDD transmission is achieved using both 29-GBaud PAM4 and 30-Gbps NRZ formats over 10 km of standard SMF. BER as low as 10^{-8} for PAM4 and 10^{-6} for NRZ are obtained, well below typical FER thresholds, with open eye diagrams that closely resemble back-to-back performance. These results confirm the feasibility and robustness of wafer-scale AlN-based frequency combs as compact, cost-effective multi-wavelength sources for high-speed optical interconnects. The demonstrated performance highlights the potential of CMOS-compatible AlN photonics for scalable data-transmission systems in future data-center and communication applications.

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