Wavelength Conversion of 10-Gb/s RZ-OOK Using Filtered XPM in a Passive GaAs–AlGaAs Waveguide

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***Abstract*—Wavelength conversion of a 10-Gb/s return-to-zero on–off-keyed (RZ-OOK) signal has been achieved using transient cross-phase modulation in a passive GaAs–AlGaAs bulk-waveguide, followed by a detuned filter. The converted RZ-OOK signal showed a power penalty of <1 dB at a bit-error-rate of 10^{-9} relative to the baseline RZ-OOK signal.**

***Index Terms*—Nonlinear optics, optical frequency conversion, optical Kerr effect, optical propagation in nonlinear media, optical waveguides.**

I. Introduction

WAVELENGTH conversion (WC) by transient cross-phase modulation (XPM-WC) and detuned filtering has been successfully carried out in compact, semiconductor devices such as semiconductor optical amplifiers (SOAs) [1], [2], and silicon nanowire waveguides [3]. For SOAs in particular [1], [2], it was possible to achieve a switching speed more than 30 times faster than the SOA gain recovery time [1], [2]. However, while SOAs are widely used in such experiments due to the potential for signal gain, they are more difficult to fabricate and package than simple passive waveguides. An SOA is also an active device that requires current-injection circuitry, temperature control, and is difficult to integrate with passive waveguide structures. Passive nonlinear waveguides, such as silicon nanowires [3], [4], AlGaAs nanowires [5], or chalcogenide glass waveguides [6], [7] could provide simpler solutions that require no control electronics. Yet, nano-scale waveguides can also be challenging to fabricate, requiring high-resolution lithography and additional processing for integrated mode-adapters to facilitate coupling to fibers.

Another candidate for XPM-WC may be the passive GaAs–AlGaAs bulk-waveguide. Since GaAs is a direct-bandgap semiconductor unlike crystalline Si (c-Si), its nonlinear index (1.59×10^{-13} cm^2/W) is significantly larger than that (0.45×10^{-13} cm^2/W) of c-Si [8], which can relax fabrication processes, and facilitate coupling to fiber (thus obviating the need for complex, integrated mode-adapters). WC by four-wave mixing has been previously demonstrated in a GaAs–AlGaAs microring resonator [9]. In this report, a GaAs–AlGaAs bulk-waveguide that was fabricated in a single lithographic step was used for XPM-WC. Although there have been rigorous, receiver sensitivity measurements on XPM-WC in SOAs, there have been no reports of such experiments using passive semiconductor devices such as Si nanowires [10], or GaAs–AlGaAs bulk-waveguides. We report, for the first time to our knowledge, XPM-WC on 10-Gb/s return-to-zero on–off-keyed (RZ-OOK) data using a passive GaAs–AlGaAs bulk-waveguide followed by a detuned filter, evaluated in a receiver sensitivity experiment. A conversion penalty <1 dB was achieved at 10^{-9} BER.

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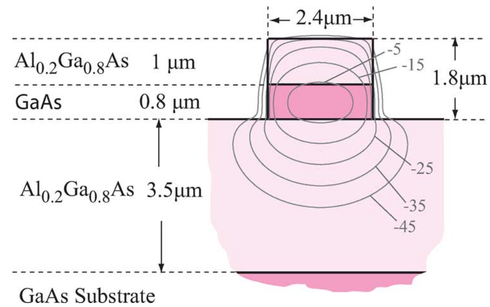

Fig. 1. Cross-section of the GaAs–AlGaAs bulk-waveguide, showing a decibel-contour plot of the quasi-transverse-electromagnetic (QTE) mode field.

II. Experiment and Discussion

The device used in the experiment is a GaAs–AlGaAs ridge waveguide (Fig. 1). Its epistructure was grown by metal–organic chemical vapor deposition, on a n-GaAs substrate, and comprised a 3.5-μm-thick $Al_{0.2}Ga_{0.80}As$ buffer, a 0.8-μm-thick GaAs guiding layer, and a 1-μm-thick $Al_{0.2}Ga_{0.80}As$ cladding. A 2.4-μm-wide ridge waveguide was fabricated in a single contact-photolithographic step, followed by an inductively coupled plasma etch to a depth of 1.8 μm, using a BCl_3/Cl_2 gas mixture. The waveguide was cleaved to a length of 0.45 cm. The waveguide operates in TE-mode with an estimated propagation loss of 6 dB/cm. The effective area was estimated to be 1.8 μm^2, which together with a nonlinear index of 1.59×10^{-13} cm^2/W [8], yield a nonlinear coefficient of approximately 36 W^{-1}m^{-1} at 1550 nm.

The experimental setup for the XPM-WC experiment is shown in Fig. 2. A 3-ps-pulsed 1553.5-nm 10-GHz

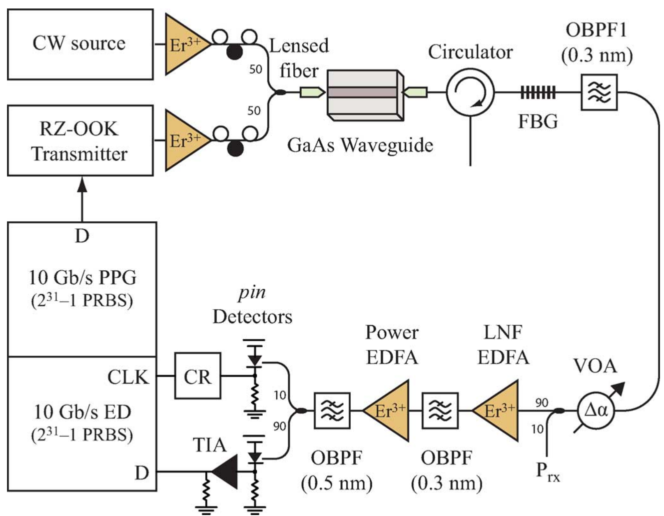

Fig. 2. Experimental setup: PPG: Pulsed-pattern generator. D: Data. EDFA: Er-doped fiber amplifier. OBPF: Optical band-pass filter. FBG: Fiber Bragg grating notch filter. VOA: Variable optical attenuator. $P_{\rm rx}$: Receiver power. LNF: Low-noise figure. CR: Clock recovery. CLK: Clock. TIA: transimpedance amplifier. ED: error detector.

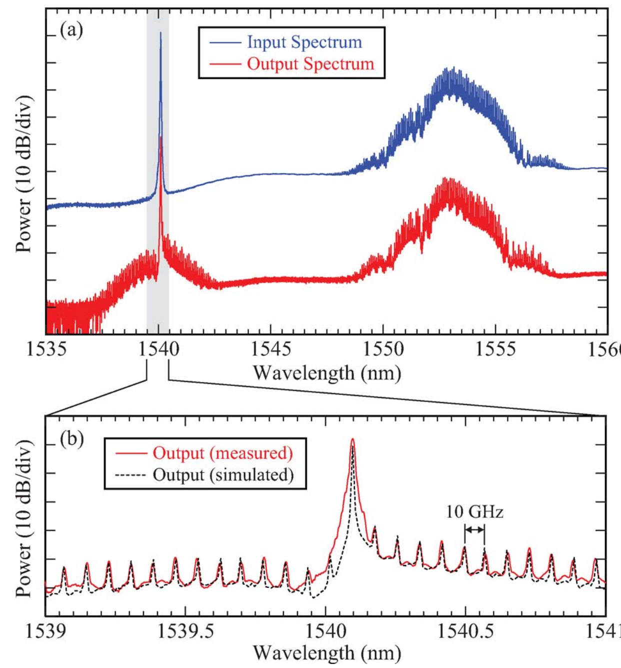

Fig. 3. (a) Spectra collected before the waveguide (blue, upper trace) and after the waveguide (red, lower trace). The resolution bandwidth (RB) of the optical spectrum analyzer (OSA) was 10 pm. The spectra have been vertically offset for clarity. (b) Magnified spectrum of the measured output cross-phase modulated CW signal (solid line) and numerically simulated output spectrum (dashed line).

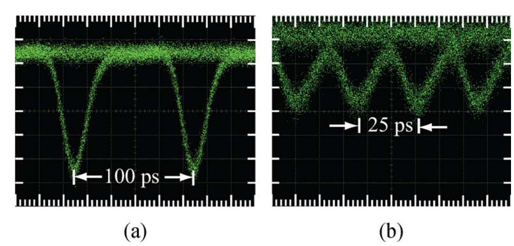

Fig. 4. The 60-GHz sampling oscilloscope traces of the probe, filtered to show XAM: (a) 10 Gb/s (20 ps/div.), and (b) 40 Gb/s (10 ps/div.) The average pump power was 22 dBm for both cases.

mode-locked laser diode was modulated with a $2^{31}-1$ pseudorandom binary sequence (PRBS) in a lithium niobate amplitude modulator, to produce the RZ-OOK pump. The RZ-OOK pump and the 1540-nm continuous-wave (CW) probe were then amplified and injected into the waveguide using a 50% coupler. The respective pump and probe average input powers were 19 and 17 dBm, measured at the input lensed fiber. The total waveguide insertion loss was 13 dB (measured using an input CW power of -20 dBm), which includes an estimated coupling loss of 5 dB/facet. The probe output by the waveguide was isolated and processed with filters. The rest of the experimental setup constituted a standard preamplified receiver.

In Fig. 3(a), we show the spectra captured at the input and the output of the waveguide. The output probe acquired a spectral pedestal due to the combined effects of XPM and cross-absorption modulation (XAM). Fig. 3(b) shows an enlarged plot of the output probe spectrum. The asymmetry in the spectral pedestal is explained by free-carrier dispersion (FCD), resulting from carriers generated by degenerate two-photon absorption (D-TPA) of the strong pump pulses. The dashed curve in Fig. 3(b) shows the numerically calculated output spectrum, including both the Kerr effect (n_2) and FCD. By matching the experiment and simulation, we estimate that the free-carrier effect contributed a maximum phase shift of -0.10π radians per pump pulse, while the Kerr effect induced a peak phase shift of $+0.35\pi$ radians per pump pulse.

To further explore the role of free carriers, we increased the pump power from 19 to 22 dBm, tuned all of the optical filters for maximum transmission of the probe, and bypassed the FBG notch filter. Fig. 4(a) plots the resulting eye diagram of the received signal, measured using a 60-GHz sampling oscilloscope. The signal intensity exhibits dips caused by pump-induced XAM. The eye diagram shows little evidence of a slow recovery associated with free-carrier absorption, which suggests that nondegenerate TPA is the dominant XAM mechanism. The experiment was also repeated using a 3-ps-pulsed 40-Gb/s $2^{31}-1$ PRBS RZ-OOK pump [Fig. 4(b)], and once again demonstrated full recovery in the XAM-probe.

Fig. 5 summarizes the XPM-WC process in the spectral domain, which demonstrates the pedestal in the probe due to D-TPA and the Kerr effect. Because the FBG was not tunable, the probe carrier was instead detuned by -0.5-nm relative to the composite filter. The composite filter responsible for the conversion of the XPM-induced phase modulation to amplitude modulation, was synthesized by detuning the filters used in the setup (Fig. 2), in conjunction with the FBG notch filter. The respective -3- and -6-dB bandwidths of the composite filter were 0.17 and 0.26 nm. The steep transmission characteristic of this filter's transfer function mediated the conversion of the XPM-induced phase modulation to amplitude modulation, while simultaneously suppressing the probe's carrier (circled in red in Fig. 5) by $\approx$30 dB relative to the apex of the converted probe (resolution bandwidth $(\text{RB}) = 10$ pm). The out-of-band rejection for the composite filter is estimated to

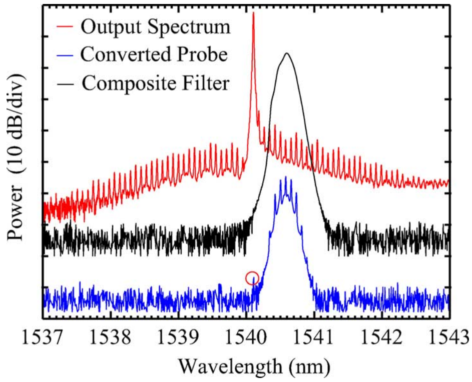

Fig. 5. Spectral conversion of the CW probe to RZ-OOK (OSA RB = 10 pm). The residual carrier in the converted probe has been circled in red. The spectra have been offset for clarity.

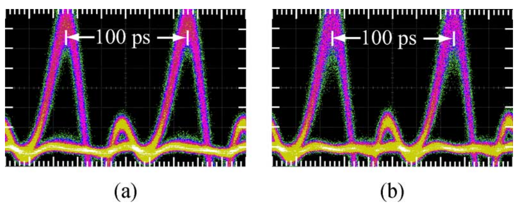

Fig. 6. Infinite-persistence 10-Gb/s sampling oscilloscope traces: (a) RZ-OOK pump, and (b) converted probe. Receiver power ($P_{\rm rx}$) was -35 dBm, and the power into the sampling oscilloscope was ≈ -3 dBm, for each case. The artifact in the zero rails is ascribed to the sampling module's RF response. The time axis was set to 20 ps/division for both traces.

be ≈60 dB (RB = 10 pm). Fig. 6 shows the pump and the converted probe, each captured immediately before the receiver detector, and at a receiver power of -35 dBm. Clearly, the data was efficiently transferred from the pump to the CW probe. However, the pulsewidth of the converted probe was different from that of the pump due to the interaction of the probe with the composite filter. The pulsewidth broadening was found to be no more than 20% (measured prior to detection in the receiver), and confirmed with autocorrelation measurements on the signals in Fig. 6, yielding respective pump and converted probe full-width-at-half-maximum pulsewidths of ≈17 and ≈19 ps. The pulsewidths were significantly larger than that (3 ps) of the original pump, due to convolutions with the receiver filters. However, no receiver sensitivity penalty due to pulsewidth broadening was expected for the converted probe. Fig. 7 summarizes the preamplified receiver sensitivity measurements. The baseline RZ-OOK pump receiver sensitivity was ≈ -37 dBm at 10^{-9} BER, and was measured by bypassing the waveguide chip, and the FBG in Fig. 2, and tuning the remaining filters to the pump wavelength. The converted RZ-OOK probe was ≈0.7 dB worse at 10^{-9} BER.

III. Summary and Conclusions

XPM-WC of 10-Gb/s RZ-OOK data has been carried out for the first time using a passive GaAs–AlGaAs bulk-waveguide, and a detuned filter. The 10^{-9}-BER receiver sensitivity degradation was <1 dB for the converted probe relative to the (baseline RZ-OOK) pump. The technique may be scalable to data rates >10 Gb/s, since it utilizes the transient XPM effect, which depends on the rise-time of the pump pulse and the steepness in the filter's edge [1], [2]. However, since the conversion filter has to be offset relative to the probe carrier, the converted-probe's optical signal-to-noise ratio will place an upper bound on data-rate scalability.

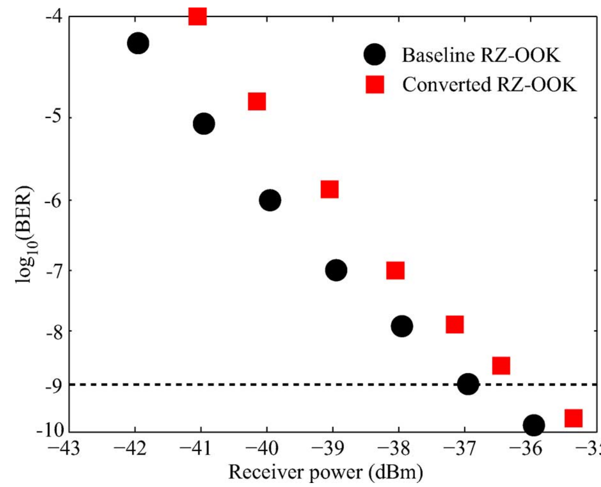

Fig. 7. Receiver sensitivity measurement results. The slight divergence between the two curves is due to drift in waveguide coupling.

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