Low-Power All-Optical Gate Based on Sum Frequency Mixing in APE Waveguides in PPLN

K. R. Parameswaran, M. Fujimura, M. H. Chou, and M. M. Fejer

***Abstract*—We present an all-optical gate implemented in periodically poled lithium niobate. Efficient mixing is achieved by using a phase-matched guided-wave interaction. A control wave at 1.537 μm is used to gate a signal at 1.552 μm, where a control power of 185 mW is sufficient to achieve 96% depletion of a low-power signal. A simple switch configuration is described whereby high-contrast low-power all-optical switching can be performed.**

***Index Terms*—Gated mixer, nonlinear optics, optical fiber communications, optical frequency conversion, optical switching, optical waveguide, periodically poled lithium niobate, quasi-phase-matching, sum frequency generation.**

I. INTRODUCTION

ALL-OPTICAL switching is an enabling function for future high-speed fiber communication systems. Previously demonstrated approaches using the third-order material nonlinearity $\chi^{(3)}$ suffer from difficulties such as high-switching powers and/or long devices (due to weak nonlinearities in optical fiber-based four wave mixing [1]) or signal degradation due to additive noise (in four wave mixing in semiconductor optical amplifiers (SOA's) [2]. Cascading of second-order nonlinearities $(\chi^{(2)} : \chi^{(2)})$ has also been used to perform switching [3]. The switching power needed in these configurations is quite high (on the order of several Watts), primarily because they operate far from phase matching in order to simultaneously obtain a large phase shift (required for switching) and flat spectral response.

We demonstrate an all-optical gate based on sum frequency mixing (SFM) using a single $\chi^{(2)}$ interaction in an annealed proton exchanged (APE) waveguide formed in periodically poled lithium niobate (PPLN). This approach exploits the high conversion efficiency available from a phase-matched interaction, resulting in 96% depletion of a CW signal by a 185-mW control beam. A structure using this gate is described with which high-contrast low-power, all-optical switching can be performed.

II. THEORY

Coherent three-wave mixing using $\chi^{(2)}$ has several attractive features such as transparency to signal format and the addition of negligible excess noise. Difference frequency mixing (DFM) using $\chi^{(2)}$ has been used to perform efficient wavelength conversion within the 1.55-μm communication band [4] as well as between the 1.3- and 1.55-μm bands [5]. In each case, a strong pump wave is mixed with weak signal waves to produce mixed outputs at frequencies mirrored about half the local oscillator frequency. These same devices can be used to mix a low-power signal with a stronger control wave to generate a signal at the sum frequency. Both phenomena are described by the well-known coupled mode equations for three-wave mixing [6], but with different boundary conditions in each case. In DFM, the low-power signal is *amplified* during the mixing process, whereas in SFM, the signal wave is *depleted* during generation of the sum frequency wave. In the simple case of a phase-matched interaction without loss, where the control wave is much stronger than the signal wave (and can be considered undepleted), the evolution of power in the SFM and signal waves is described by

$$P_{\mathrm{SFM}}(L) = P_{\mathrm{SIG}}(0)\,\frac{\lambda_{\mathrm{SIG}}}{\lambda_{\mathrm{SFM}}}\,\sin^2(\sqrt{\eta_{\mathrm{nor}} P_{\mathrm{CTRL}}}L) \qquad (1a)$$

$$P_{\mathrm{SIG}}(L) = P_{\mathrm{SIG}}(0)\cos^2(\sqrt{\eta_{\mathrm{nor}} P_{\mathrm{CTRL}}}L) \qquad (1b)$$

where L is the interaction length, P_{CTRL} is the control power, λ_{SFM} and λ_{SIG} are the SFM and signal wavelengths and η_{nor} is the normalized conversion efficiency. Complete depletion of the signal occurs when the argument of the trigonometric functions equals $\pi/2$. Hence, gating of the signal can be accomplished by turning the control power on and off.

III. EXPERIMENT

The device used in this work was designed to mix signal and control waves in the 1.55-μm band, with a mixing region designed to be insensitive to variations in waveguide width, which loosens fabrication tolerances [7]. This noncritical design requires a waveguide that supports multiple transverse modes at both input wavelengths in the conversion region, so a mode filter and adiabatic taper at the input are incorporated to facilitate launching of power into the fundamental modes in the conversion region [8]. The optimized widths are 4 μm for the mode filter and 12 μm for the conversion region. The 6.05-cm long sample was diced from a 3-in-diameter wafer of $\mathrm{LiNbO_3}$, which had been electric-field poled [9] with a quasi-phasematching

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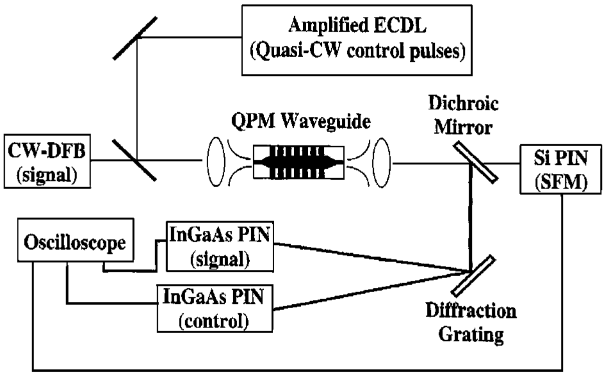

Fig. 1. Experimental setup.

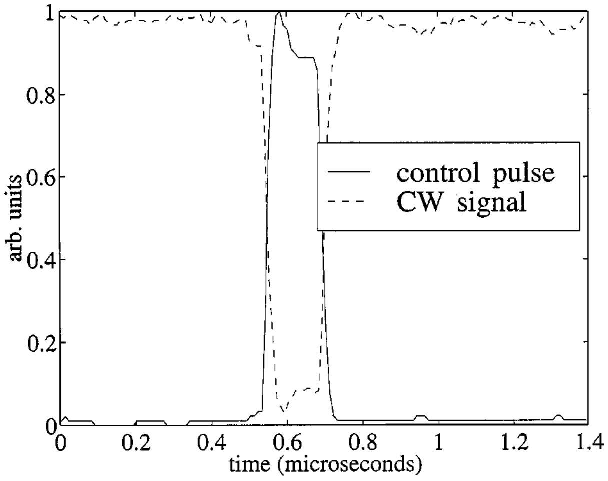

Fig. 2. Typical pulse traces, showing depletion of the signal in the presence of the control pulse.

(QPM) period of 14.7 μm. The QPM grating is 5.55 cm long. Waveguides were formed by proton exchange for 15 h at a temperature of 160 °C (to a depth of 0.71 μm), followed by annealing for 26 h at 328 °C. The end faces of the sample were then polished to permit efficient end fire coupling.

The experimental setup is shown in Fig. 1. Control pulses were produced by a fiber-amplified externally modulated diode laser. A DFB laser diode operating at 1.552 μm produces the CW signal. Phasematching was observed with $\lambda_{\mathrm{CTRL}} = 1.537$ μm resulting in $\lambda_{\mathrm{SFM}} = 0.772$ μm. The signal and control beams are combined, then launched into the same waveguide. Output light at the three wavelengths is separated using a dichroic mirror and diffraction grating, then directed onto fast photodiodes for power measurement. The experiment was carried out at room temperature.

IV. RESULTS AND DISCUSSION

Fig. 2 shows depletion of the CW signal in the presence of the control pulse. One advantage of the nonlinear transfer function of the SFM process is that distortions in the control pulse are suppressed in the depleted signal pulse, making the switching less sensitive to variations in the control pulse. Fig. 3 shows a plot of normalized signal transmission as a function of control power. The solid line shows the calculated result obtained by numerical integration of the coupled mode equations describing the SFM process in waveguides, including the propagation losses neglected in obtaining (1). The calculation used a normalized internal SFM conversion efficiency of 33.9 W^{-1} (as determined by measurement of the second harmonic generation efficiency of 8.47 W^{-1}) and typical values of propagation losses at the three wavelengths (0.35 dB/cm at λ_{SIG} and λ_{CTRL}, and 0.70 dB/cm at λ_{SFM}). Mode profiles used in the calculation were obtained by solution of Maxwell's equations subject to the refractive index profile resulting from the annealed proton exchange process [16]. Nearly complete (96%) extinction of the signal is seen at an input control power of 185 mW, a value in reasonable agreement with theory. The mechanism responsible for the residual 4% is unclear; slight phase mismatch arising from waveguide nonuniformity is one possibility.

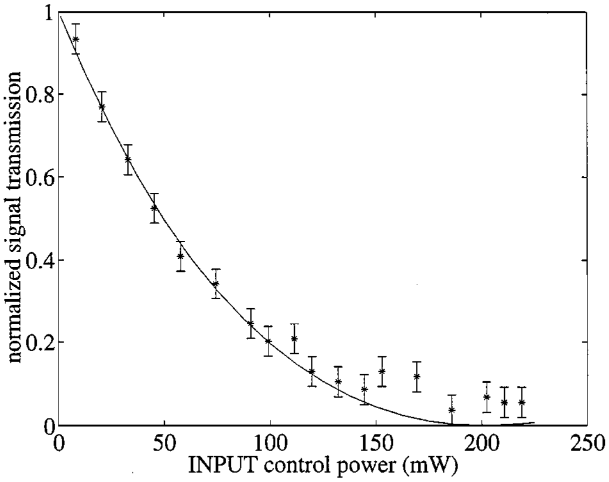

Fig. 3. Measured and calculated variation of signal transmission with control power.

V. FUTURE POSSIBILITIES

The required gating power in SFM devices can be significantly reduced by several relatively straightforward means. The device used in this experiment had nonuniformities resulting from imperfect fabrication. Optimization of the process would result in a 30% increase in η_{nor}. The conversion efficiency in waveguide QPM interactions is roughly proportional to the square of the grating length. Periodically poled devices as long as 8 cm have been reported [10], hence, moving to this length from the current value of 5.55 cm would increase η_{nor} by about a factor of two. High index cladding layers [11] and buried waveguides [17] have also been used to improve the spatial overlap of modes in waveguides. Calculations indicate that this technique could potentially increase η_{nor} by another factor of two. Combining the above techniques could result in a control power around 40 mW (or 16 dBm, a power level readily available from commercial EDFA's). This corresponds to a gating energy of 1 pJ for 25 ps pulses in a 20-GHz return-to-zero pulse train, which compares very well with similar experiments using SOA's [12]. The bandwidth of the device is limited by group velocity walkoff between the three interacting waves such that the minimum pulsewidth scales inversely with the device length. Hence, efficiency and bandwidth can be traded against

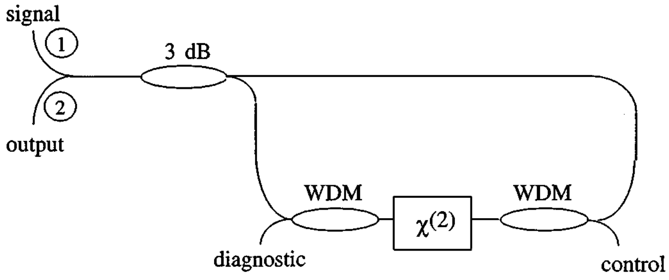

Fig. 4. "AND" gate using $\chi^{(2)}$ in NOLM configuration.

each other. One way to eliminate this tradeoff is known as "quasi-group velocity matching" [8], where after each walkoff length, the faster pulse passes through a delay line integrated into the waveguide structure in order to be resynchronized with the slower pulse. This scheme, currently being investigated, would allow for high efficiency switching of "arbitrarily" short pulses.

VI. PROPOSED SWITCH STRUCTURE USING $\chi^{(2)}$ GATE

Higher contrast can be achieved by placing this device in an interferometer or in a nonlinear optical loop mirror (NOLM [13], Fig. 4). In the absence of the control pulse, the loop is balanced and all of the signal power exits at port 1. When the control is on, signal power traveling in one direction in the loop gets depleted so that incomplete interference at the 3-dB coupler results in signal power leaving port 2 (at a level 6 dB below the input value). Hence, an "AND" logic function is implemented (there is output only when the signal and control are both on). Power switched to the SFM wave (at 0.772 μm in the current device) can be used for further signal processing. A similar device has been used to perform efficient optical sampling [14].

An attractive feature of SFM is that the signal wavelength acceptance bandwidth is narrow (~0.3 nm for a 6 cm long device) such that individual WDM channels can be switched out of a bit stream in this way. In order to switch multiple wavelengths simultaneously, DFM can be used as the mixing process instead of SFM. Here, the NOLM is unbalanced by *amplifying* the signal rather than switching it out. Parametric gain on the order of 3 dB has been observed in APE waveguides in PPLN [15]. This can be used to create a switch with 0-dB insertion loss and very wide signal bandwidth (around 46 nm, for a 6-cm device).

VII. CONCLUSION

An optical gate based on phasematched SFM in QPM-APE waveguides in PPLN has been demonstrated. Nearly complete extinction with a control power of 185 mW was observed. Two possible configurations for very high contrast switching have been presented.

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REFERENCES

[1] S. Bigo, O. Lerclerc, and E. Desurvire, "All-optical fiber signal processing and regeneration for soliton communications," *IEEE J. Selected Topics Quant. Electron.*, vol. 3, pp. 1208–1223, 1997.

[2] D. F. Geraghty, R. B. Lee, K. J. Vahala, M. Verdiell, M. Ziari, and A. Mathur, "Wavelength conversion up to 18 nm at 10 Gb/s by four-wave mixing in a semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 452–454, 1997.

[3] Y. Baek, R. Schiek, G. I. Stegeman, G. Krinjen, I. Baumann, and W. Sohler, "All-optical integrated Mach–Zender switching due to cascaded nonlinearities," *Appl. Phys. Lett.*, vol. 68, pp. 2055–2057, 1996.

[4] M. H. Chou, J. Hauden, M. A. Arbore, and M. M. Fejer, "1.5 μ m band wavelength conversion based on difference frequency generation in $LiNbO_3$ waveguides with integrated coupling structures," *Opt. Lett.*, vol. 23, pp. 1004–1006, 1998.

[5] M. H. Chou, K. R. Parameswaran, M. A. Arbore, J. Hauden, and M. M. Fejer, "Bidirectional wavelength conversion between 1.3- and 1.5-μm telecommunication bands using difference frequency mixing in $LiNbO_3$ wavegudes with integrated coupling structures," *CLEO 1998*, pp. 475–476.

[6] R. W. Boyd, *Nonlinear Optics*. New York: Academic, 1992.

[7] M. L. Bortz, S. J. Field, M. M. Fejer, D. W. Nam, R. G. Waarts, and D. F. Welch, "Noncritical quasiphase matched second harmonic generation in an annealed proton-exchanged $LiNbO_3$ waveguide," *IEEE Trans. Quantum Electron.*, vol. 30, pp. 2953–2960, 1994.

[8] M. H. Chou, "Optical frequency mixers using three-wave mixing for optical fiber communications," Ph.D. dissertation, Stanford Univ., 1999.

[9] L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, W. R. Bosenberg, and J. W. Pierce, "Quasiphase-matched optical parametric oscillators in bulk periodically poled $LiNbO_3$," *J. Opt. Soc. Amer. B*, vol. 12, pp. 2102–2116, 1995.

[10] D. Hofmann, G. Schreiber, C. Haase, H. Herrmann, W. Grundkötter, R. Ricken, and W. Sohler, "Quasiphase-matched difference-frequency generation in periodically poled Ti:LiNbO3 waveguides," *Opt. Lett.*, vol. 24, pp. 896–898, 1999.

[11] K. Mizuuchi, H. Ohta, K. Yamamoto, and M. Kato, "Second-harmonic generation with a high-index-clad waveguide," *Opt. Lett.*, vol. 22, pp. 1217–1219, 1997.

[12] B. K. Mathason, H. Shi, I. Nitta, G. A. Alphonse, J. Abeles, J. C. Connolly, and P. J. Delfyett, "Multiwavelength all-optical TDM switching using a semiconductor optical amplifier in a loop mirror," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 331–333, 1999.

[13] K. J. Blow, N. J. Doran, and B. P. Nelson, "Demonstration of the nonlinear fiber loop mirror as an ultrafast all-optical demultiplexer," *Electron. Lett.*, vol. 26, pp. 962–964, 1990.

[14] T. Suhara, H. Ishizuki, M. Fujimura, and H. Nishihara, "Waveguide quasi-phase-matched sum-frequency generation device for high-efficiency optical sampling," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1027–1029, 1999.

[15] M. H. Chou, I. Brener, G. Lenz, R. Scotti, E. E. Chaban, J. Shmulovich, D. Philen, S. Kosinski, K. R. Parameswaran, and M. M. Fejer, "Efficient, wideband, and tunable mid-span spectral inverter using cascaded nonlinearities in $LiNbO_3$ waveguides," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 82–84, 2000.

[16] M. L. Bortz, "Quasi-phasematched optical frequency conversion in lithium niobate waveguides," Ph.D. dissertation, Stanford Univ., Stanford, CA, 1994.

[17] Y. N. Korkishko, V. A. Fedorov, T. M. Morozova, F. Caccavale, F. Gonella, and F. Segato, "Reverse proton exchange for buried waveguides in $LiNbO_3$," *J. Opt. Soc. Amer. A*, vol. 15, pp. 1838–1842, 1998.