Wavelength-Selective Pulsed All-Optical Switching Based on Cascaded Second-Order Nonlinearity in a Periodically Poled Lithium–Niobate Waveguide

G. S. Kanter, P. Kumar, K. R. Parameswaran, and M. M. Fejer

***Abstract*—We report all-optical switching in a time and wavelength window based on cascaded sum- and difference-frequency generation in a periodically poled lithium-niobate waveguide. More than 50% switching of a 5-ps pulse is observed with a gate-pulse peak power of 6.6 W.**

***Index Terms*—Nonlinear optics, optical communications, optical switches, optical waveguides.**

CASCADED second-order ($\chi^{(2)}$) nonlinear effects have been proposed for many functions, including spectral inversion, optical transistors, and all-optical switching [1]–[3]. Often, cascaded $\chi^{(2)}$ phenomena can be viewed as mimicking the kind of $\chi^{(3)}$ effects found in optical fibers. However, since the effective n_2 can be orders of magnitude larger than that in fiber, the cascaded $\chi^{(2)}$ phenomena can be exploited to create compact, low-latency devices.

Sum-frequency generation (SFG) and difference-frequency generation (DFG) can be used to create an optically gated three terminal switch. Such a device works most efficiently at phase matching [4]. In this case, the signal is first completely converted into the sum frequency, and it then experiences a π phase shift when it is regenerated via DFG. A phase shift can also accrue away from phase matching; here the transfer of power between the signal and sum frequencies occurs more frequently than in the phase matched case, but the magnitude of the phase shift is smaller. The effective nonlinearity associated with the phase shift increases as the phase matching condition is approached.

It is at phase matching that previous SFG/DFG-based switches have been demonstrated, first in bulk lithium niobate (LN) with 1-ns signal pulses [4], and then in a periodically poled LN (PPLN) waveguide with a continuous wave (CW) signal (6-ps gate pulse) [5]. Recently, a low-power all-optical gate was also demonstrated [6], wherein SFG was used to remove (gate) the CW signal.

In this letter, we demonstrate true high-speed operation of a SFG/DFG switch, using 5-ps pulses for both the signal and the gate beams. Additionally, we have recorded the switching characteristics as a function of the signal wavelength. Due to the phase-matching constraint, only pulses in a certain wavelength window can be switched at one time. Because this window can be tuned by changing the pump-pulse wavelength, or the temperature of the PPLN waveguide, such a switch can potentially be used to drop/demultiplex one time slot from a single, reconfigurable wavelength in a TDM/WDM communications line of terabits per second aggregate bit rate.

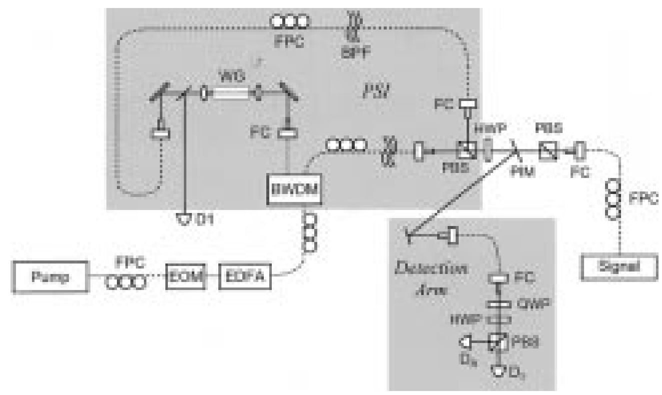

Fig. 1. A schematic of the optical switching experiment. Optical fiber is designated by dotted lines and solid lines represent light path in free space.

A schematic of our experimental setup is shown in Fig. 1. The signal pulses enter a polarization Sagnac interferometer (PSI) containing the PPLN waveguide (WG), which is configured to split the signal light equally into the clockwise and counterclockwise directions by use of a half-wave plate (HWP) and a polarizing beam splitter (PBS). Most of the reflected signal light (the output of the PSI) is tapped off by a partially-reflecting, polarization-insensitive mirror (PIM) into the detection arm. Another HWP and a quarter-wave plate (QWP) placed before the photodetectors are adjusted such that in the absence of the pump pulses the reflected light hits only one of the two detectors (D_R). We call the port with D_R (D_T) the mirror (switching) port of the PSI.

The pump pulses are combined with the signal pulses (traveling from right to left in the waveguide in Fig. 1) with use of a fiber-optic broad-band WDM (BWDM). The presence of the pump affects both the magnitude and phase (due to cascaded SFG/DFG) of the copropagating signal. As a result the PSI gets unbalanced, changing the state of polarization of the signal pulses at the output of the PSI. This in turn causes a change in the relative powers detected by D_R and D_T. Ideally,

Manuscript received September 5, 2000; revised November 10, 2000. This research was supported in part by the National Science Foundation and the Air Force Office of Scientific Research.

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Publisher Item Identifier S 1041-1135(01)01971-1.

under CW operating conditions and with perfect phase matching in the waveguide, complete switching would be obtained at a certain pump power, directing all the reflected signal light from the mirror port (D_R) to the switching port (D_T).

The waveguide used in this work was fabricated using electric-field poling [7], followed by annealed proton exchange (APE) [8]. The end faces of the 2.5-cm-long waveguide were then polished and antireflection coated. To optically characterize the performance of the waveguide, we measured its tuning curve for second-harmonic generation (SHG) in the low-conversion-efficiency limit, which is shown in Fig. 3(a). The peak conversion efficiency (ratio of the harmonic output power to the square of the fundamental output power exiting the waveguide) was $\simeq$ 200%/W. The large sideband peaks (compared to an ideal sinc-squared profile) are due to inhomogeneous phase matching, probably caused by slight variations in the waveguide width which can occur in the fabrication process.

Because the APE waveguides only guide the TM-polarized mode, fiber polarization controllers (FPCs) are used to maximize coupling of the signal, and to control the amount of the pump power coupled into the waveguide. Typically, $\simeq 5$ μW (average power) of the signal (in each direction) and 60–800 μW of the pump are coupled into the guide. A beam splitter is used to direct 3% of the transmitted pump power to detector D1 in order to characterize the coupled pump power. Tunable bandpass filters (BPFs) are used to remove the pump light. Two such filters are used so that small backreflections from the AR-coated guide wouldn't corrupt the measurements.

In our experiment, the pump and signal pulses are generated by two tunable passively modelocked fiber lasers that are synchronized by injection locking one with the other [9]. The laser outputs are 14-MHz trains of $\simeq$5-ps duration transform-limited pulses having sech-square intensity profiles. We use an inline electro-optic modulator (EOM) to turn the pump pulses off for a 3.5-μs time duration every 16 μs. This is done merely for convenience in order for the switching efficiency to be directly measured during the experiment. The modulated pump-pulse train is then amplified by an erbium-doped fiber amplifier (EDFA) to increase the average power. Depending on the signal wavelength, a small amount of amplified spontaneous emission (ASE) from the EDFA could reach the detection apparatus, despite our use of two inline BPFs. This leakage associated with the pump pulses, with average power always much smaller than the signal, was recorded and subtracted from the switching measurements. To maximize the switching (or, more generally, the SFG), the pump and signal pulses need to be overlapped in time to within a couple of picoseconds. This was accomplished by attaching the fiber collimator (FC) for the input signal to a translation stage, which was then moved to provide a delay (advance) to the signal pulses relative to the pump pulses.

Without the pump, approximately 96% of the output-signal power picked up by the PIM goes to the mirror port with the remaining 4% reaching the switching port. This signal leakage is due in part to: a) residual back reflections from the end faces of the AR-coated waveguide; b) the inability of the multiple-order wave plates to work equally well over the entire signal spectrum; and c) the nonidealities in the various beam splitters.

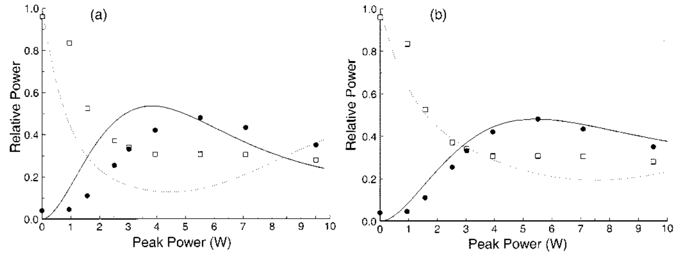

Fig. 2. Relative powers detected at the mirror port (boxes) and the switching port (circles) for a signal wavelength of 1535.6 nm (near phase matching) as the pump power is varied. Lines are results of simulations with directly and indirectly measured parameters in (a) and with adjusted parameters in (b). See text for details.

The waveguide was heated to $\simeq 85\,^{\circ}$C to phase match the SHG near 1540.55 nm. This also served to phase match the SFG with a pump at 1545.6 nm and a signal near 1535.6 nm.

The data in Fig. 2 show the switching performance for a signal near the phase-matching wavelength as the pump power is increased (the pump wavelength is 1545.6 nm). Results of numerical simulations are also plotted, which were obtained by numerically solving the coupled-mode equations with inclusion of the group-velocity mismatch [10]. The measured SHG efficiency was used to determine the needed nonlinearity constant. Other values [1] used in the program were obtained either through measurements on similar waveguides or indirectly estimated by numerically simulating the waveguide modes. The theoretical fits so obtained are shown in Fig. 2(a). Perfect phase matching has been assumed and no adjustment was made to the parameters.

Under the CW approximation with no pump depletion, the expected behavior as the pump power is increased is for the signal at the switching port to rise up to one, whereas the signal at the mirror port falls down to zero. There are several effects that diminish this ideal switching contrast. One is that both the pump and the signal pulses have approximately the same temporal width. Therefore, the pump intensity varies across the signal profile and the switching effect is temporally averaged. Using a pump pulse that is wider than the signal pulse would improve the performance. Additionally, group-velocity mismatch forces the sum-frequency pulse to walk away from the signal and pump pulses by about 3.7 ps/cm. This walk-off (over 9 ps total) is very significant for the 5-ps-wide pulses that we use and causes a severe switching-power penalty. Another possible factor is owing to deviations from uniform phase matching in the PPLN sample, as evidenced by the large side peaks in the SHG tuning curve (see Fig. 3). This last effect is not accounted for in our simulations and perhaps is the reason for the discrepancy of the simulations with the data. In Fig. 2(b), we fit the data with simulation results assuming an SHG efficiency of 150%/W and a phase mismatch of $\Delta kL = -2.5$, values which are within the margins of error. Clearly, the agreement is significantly better.

The performance near phase matching (Fig. 2) should be contrasted with that shown in Fig. 3(b), where the signal wavelength is about 2 nm away from phase matching. In this case,

[1]The simulations assume losses in the waveguide at the pump and signal wavelengths of 11%/cm and a loss of 18%/cm at the sum wavelength. The pump and signal are initially overlapped in time and propagate with equal group velocities. The generated sum pulse is slower by 3.7 ps/cm.

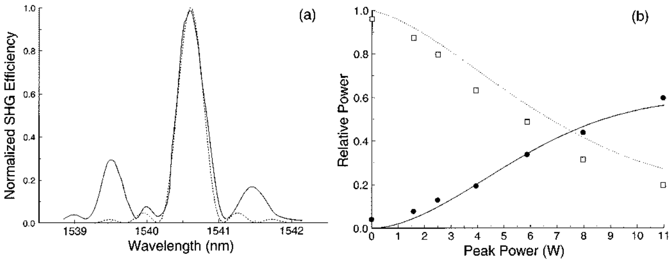

Fig. 3. (a) SHG tuning curve for the waveguide used in the experiment (solid line). The data was taken by using a tunable external-cavity semiconductor laser under conditions of low conversion efficiency. The peak conversion efficiency is $\simeq$200%/W. The dotted curve is the theoretically expected shape. (b) Relative powers detected at the mirror port (boxes) and the switching port (circles) for a signal wavelength of 1537.7 nm as the pump power is varied. Lines are results of simulations with the same parameters as in Fig. 2(b), but with phase mismatch $\Delta kL = 9$.

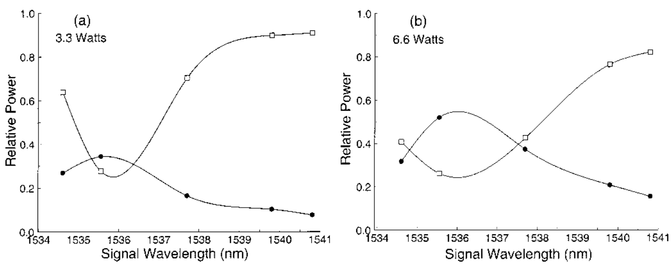

Fig. 4. Plots of the mirror-port (boxes) and switching port (circles) relative powers for peak pump powers of 3.3 W (a) and 6.6 W (b) as the signal wavelength is varied. The lines are just for guiding the eye. The switching is clearly much larger near phase matching and falls of quickly as the signal wavelength is detuned.

the switching action occurs at a larger pump power, but displays a better contrast. The higher contrast, we believe, is because the role of nonuniform phase matching is diminished for operation at larger phase mismatch values. The data is consistent with the numerical simulations (solid and dashed curves in Fig. 3), which were obtained using the same parameters as in Fig. 2(b), but with $\Delta kL = 9$ (corresponding to the detuning of the signal from the phase-matching wavelength).

As the signal wavelength moves further away from phase matching, the switching effect continues to decrease for a fixed pump power. The switching mechanism becomes almost entirely a phase-shift effect induced by the pump in contrast to both intensity modulation and nonlinear phase shift closer to phase matching. Fig. 4(a) shows the mirror- and switching-port transmissivities at several signal wavelengths for a peak pump power of 3.3 W. The switching is strong near phase matching, but falls off quickly as the wavelength is detuned. A similar plot for 6.6 W of pump power is shown in Fig. 4(b) to demonstrate how the detuning performance varies with the peak pump power. The wavelength selective nature of the device is apparent.

In conclusion, we have demonstrated all-optical switching based on cascaded SFG and DFG under various phase-matching conditions. Both the signal and gate waves were pulses of 5 ps duration. Despite substantial walk-off of the SFG pulse in our 2.5-cm-long PPLN waveguide, we observed good switching characteristics, achieving $>50\%$ switching near phase matching with 6.6 W of peak pump power. We have documented the expected degradation of the switching efficiency as the phase mismatch is increased. Low latency, wavelength-selective, high-speed switching obtained by means of the PPLN-waveguide device would be useful for optically demultiplexing TDM/WDM data in all-optical networks.

ACKNOWLEDGMENT

The authors would like to thank L. Wang for making the synchronous lasers available for the experiment and A. Agarwal for helpful discussions.

REFERENCES

[1] 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 wide-band and tunable midspan spectral inverter using cascaded nonlinearities in $LiNbO_3$ waveguides," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 62–84, Jan. 2000.

[2] D. J. Hagan, Z. Wang, G. I. Stegeman, and E. W. Van Stryland, "Phase-controlled transistor action by cascading of second-order nonlinearities in KTP," *Opt. Lett.*, vol. 19, pp. 1305–1308, Sept. 1994.

[3] C. N. Ironside, J. S. Aitchison, and J. M. Arnold, "An all-optical switch employing the cascaded second-order nonlinear effect," *IEEE J. Quantum Electron.*, vol. 29, pp. 2650–2654, Oct. 1993.

[4] I. Yokohama, M. Asobe, A. Yokoo, H. Itoh, and T. Kaino, "All-optical switching by use of cascading of phase-matched sum-frequency generation and difference-frequency generation processes," *J. Opt. Soc. Amer. B*, vol. 14, pp. 3368–3377, Dec. 1997.

[5] H. Kanbara, H. Itoh, M. Asobe, K. Noguchi, H. Miyazawa, T. Yanagawa, and I. Yokohama, "All-optical switching based on cascading of second-order nonlinearities in a periodically poled titanium-diffused lithium niobate waveguide," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 328–330, Mar. 1999.

[6] K. R. Parameswaran, M. Fujimura, M. H. Chou, and M. M. Fejer, "Low-power all-optical gate based on sum frequency mixing in APE waveguides in PPLN," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 654–656, June 2000.

[7] M. Yamada, N. Nada, M. Saitoh, and K. Wantanabe, "First-order quasiphase matched $LiNbO_3$ waveguide periodically poled by applying an external field for efficient blue second-harmonic generation," *Appl. Phys. Lett.*, vol. 62, pp. 435–436, Feb. 1993.

[8] M. L. Bortz and M. M. Fejer, "Annealed proton-exchanged $LiNbO_3$ waveguides," *Opt. Lett.*, vol. 16, pp. 1844–1846, Dec. 1991.

[9] L. Wang, Y. Su, A. Agarwal, and P. Kumar, "Polarization insensitive widely tunable all-optical clock recovery based on AM mode-locking of a fiber ring laser," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 211–213, Feb. 2000.

[10] R. M. Rassoul, A. Ivanov, E. Freysz, and A. Ducasse, "Second-harmonic generation under phase-velocity and group-velocity mismatch: Influence of cascading self-phase and cross-phase modulation," *Opt. Lett.*, vol. 22, pp. 268–270, Mar. 1997.