Spatial ultrafast switching and frequency conversion in lithium niobate waveguide arrays

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We demonstrate phase-insensitive, ultrafast, all-optical spatial switching and frequency conversion in quadratically nonlinear waveguide arrays in periodically poled lithium niobate. Routing of milliwatt signals with wavelengths in the communication band (1550 nm) is achieved without pulse distortions by parametric interaction with a control beam with 10-W power and wavelengths near 775 nm. © 2005 Optical Society of America

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The rapidly rising amount of transmitted data in optical fiber cables demands ultrafast processing of optical signals, for which essential functions include frequency conversion and (or) spatial switching. Consequently, all-optical switches are expected to be the key components of future communication networks. These switching devices are required to operate on optical data streams of multigigabits per second that have only some milliwatt average power and wavelengths distributed in the communication band near 1550 nm.

There are a variety of guided-wave devices based on ultrafast second- $[\chi^{(2)}]$ and third- $[\chi^{(3)}]$ order optical nonlinearities by which information can be split into different output paths on demand via optical control beams. Nonlinear directional couplers, X switches, and nonlinear loop mirrors inherently have two spatially separated output ports.[1–3] Other options that involve nonlinearly induced changes in the polarization, wavelength, or arrival time of signals require additional elements such as polarizers and etalons for separating out the desired signal.[1] Despite their impressive processing speed all these procedures suffered from the small values of fast off-resonant optical nonlinearities that result in either high required peak powers or long device dwell times. Active semiconductor optical amplifiers based on complex pumping schemes have offered a drastic reduction of the control powers to some milliwatts with tens of picoseconds response times.[2,3] In parallel, different all-optical devices have been developed to shift signal wavelengths, an important function in wavelength-division multiplexing communications systems.[2,4–6] Second-order nonlinear devices that rely on sum- and (or) difference-frequency generation have been developed for this purpose.[5,6] To date, both of these functions, spatial routing and wavelength shifting, have been implemented in separate devices.

Here we report what is to our knowledge the first experimental demonstration of a recently proposed all-optical switch that is capable of performing several tasks simultaneously: not only spatial switching and wavelength conversion but also signal amplification.[7] This approach utilizes a combination of the nonlinear process of parametric amplification and difference-frequency generation and the linear characteristics of wave propagation in arrays of weakly coupled channel waveguides. Diffraction of optical beams in waveguide arrays occurs by light hopping from channel to channel. The strength and nature of the so-called discrete diffraction depends on the phase difference of the excited modes in adjacent waveguides of the array and can be simply adjusted by a slight tilt of the input beam with respect to the waveguide direction.[8,9] For particular angles diffraction can be arrested, and diffractionless propagation occurs. Additionally, the evanescent coupling between adjacent guides, which mediates the discrete diffraction, shows a strong chromatic dispersion; e.g., beams with a shorter wavelength are more strongly confined in the waveguides and consequently do not couple to neighboring channels so strongly. Thus, depending on the angle of incidence and the wavelength, beams with completely different diffraction properties can coexist in the same waveguide array. We use this property to confine a pump beam (short wavelength) in single channels, whereas the low-power signal beams (long wavelength, several channels wide) can slide across the array at angles for which there is no diffraction (see Fig. 1). At the crossing, the intersecting straight propagating pump and the tilted diffractionless signal beam interact in a $\chi^{(2)}$ parametric mixing process. Because this happens in a single guide, newly generated fields at the signal frequency spread symmetrically from this waveguide on both sides while the original channel-to-channel phase relation and therefore the directions of diffractionless propagation are maintained. Hence the process results in the amplification of the original signal beam and in the emission of an additional signal beam, which crosses

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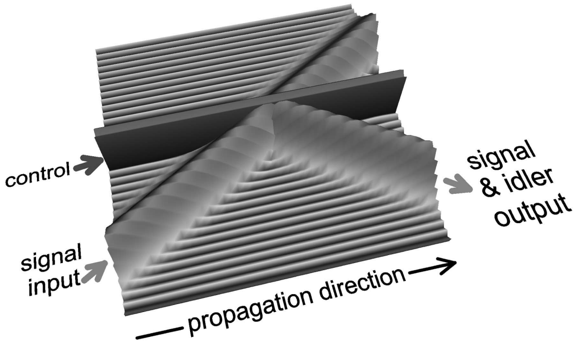

Fig. 1. All-optical switching of an input signal beam to a frequency-shifted idler at a specific output position governed by a control beam that uses parametric interaction in a quadratic nonlinear waveguide array.

the array without diffraction at the mirror angle. In addition, two more beams at the idler wavelength are generated in the parametric mixing, approximately following the path of the signal. For a small wavelength difference between signal and idler (near degeneracy), the idler's propagation is also diffractionless. As the output position and the powers of the new signal and idler beams are controlled by the input position and power of the pump beam, this beam can be called the control beam. Owing to the nondegeneracy of the parametric process, the switching is phase insensitive. It is important to note that in our specific switching scheme the nonlinearity is used only to transfer light between individual light beams of different frequencies, and the spatial switching is accomplished by the wavelength-dependent discrete diffraction phenomena of linear waves in the array. Furthermore, for low depletion of the control. Therefore spectral broadening and pulse breakup of the signal are negligible. Because $\chi^{(2)}$ can be considered an instantaneous nonlinearity, the bandwidth of the switching process is limited only by the chromatic dispersion of the wave-vector mismatch, which is the source of temporal walk-off between signal and control. However, because of the short interaction lengths involved, this is not a crucial limit.

The experiments were performed in arrays of 101, 7-μm-wide titanium indiffused waveguides with a center-to-center spacing of 13.5 μm on a 5-cm-long Z-cut lithium niobate crystal. The linear coupling length of adjacent waveguides was ≈6 mm for signal and idler. Coupling for the control was negligible. Waveguide losses were $\alpha_C = 0.4$ dB/cm and $\alpha_{S/I} = 0.2$ dB/cm. An electric field poled quasi-phase-matched grating with period $\Lambda = 16.75$ μm facilitated phase matching of the TM_{00} modes of the control, the signal, and the idler at the operation temperature of 215 °C. The elevated temperature of the sample minimized photorefractive effects. A measured second-harmonic generation efficiency of 14%/W cm^2 agrees with the theoretically expected value.

The control beam at $\lambda_C = 774.35$ nm was generated by frequency doubling of a NaCl color-center laser, giving 5-ps-long transform-limited pulses with a repetition rate of 76 MHz. To verify the phase insensitivity of the switching concept we used a different laser (tunable cw laser diode) for the signal with wavelength $\lambda_S \approx 1548.7 - \Delta$ nm. Note that the idler at $\lambda \approx 1548.7 + \Delta$ nm is shifted by 2Δ nm from the input signal's wavelength. Although using a pulsed and a cw source avoided the problem of synchronizing two pulsed lasers, it also reduced dramatically the measured efficiency of the interaction that was due to the color center's duty cycle (3.8×10^{-4}). The output of the laser diode was shaped into an elliptical beam by a cylindrical telescope and was subsequently focused by a microscope objective onto the entrance facet of the array to form a spot 3.5 μm high and 61 μm wide (FWHM). We adjusted the beam tilt to 1.6°, which corresponds to zero diffraction in the array, by shifting the beam transversely from the center of the objective to achieve a phase difference of $\pi/2$ between adjacent guides. With this simple setup the excitation efficiency of the ~4-waveguide-wide signal beam was 36%. Simultaneously the control beam was coupled into the TM_{00} mode of a single channel of the array with an efficiency of 20%.

The output from the array was characterized by spatially resolved scanning of the spectrum. A typical result is shown in Fig. 2. The signal beam was injected centered on guide 12 and exited the array centered on guide −13. With the injection of the control in guide 1, the parametrically deflected signal and idler exited the array centered on guide 15 at the output face. Scans cutting the spatially resolved spectra quantify the results in Fig. 3. Spectra of the deflected idler and signal in waveguide 15 are shown in Fig. 3(a). The spectrally narrow cw signal light that leaks from the excitation of the diffractionless propagating signal beam into the array can be distinguished from the parametrically generated pulses owing to their different spectral widths. An experimental verification of the dependence of the peak power of the generated idler on the

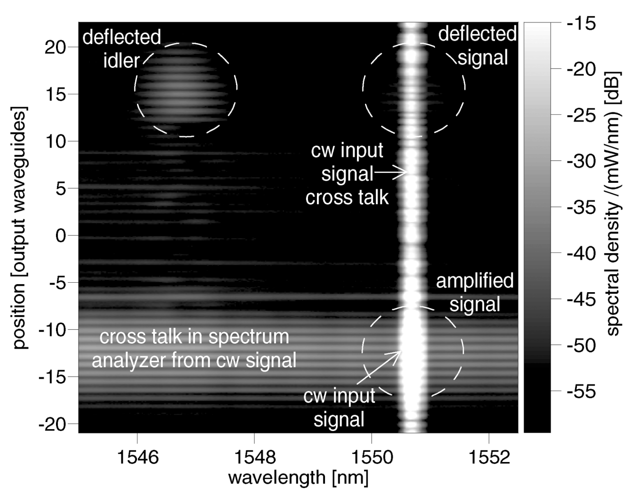

Fig. 2. Spatial spectral scan of the output of a waveguide array after parametric interaction of a signal beam ($\lambda_S = 1550.7$ nm, $P_S = 13$ mW, input centered at guide 12) and a control beam ($\lambda_C = 774.35$ nm, $P_{C\text{peak}} = 10.7$ W, input in guide 1), which generates an idler ($\lambda_I = 1546.7$ nm).

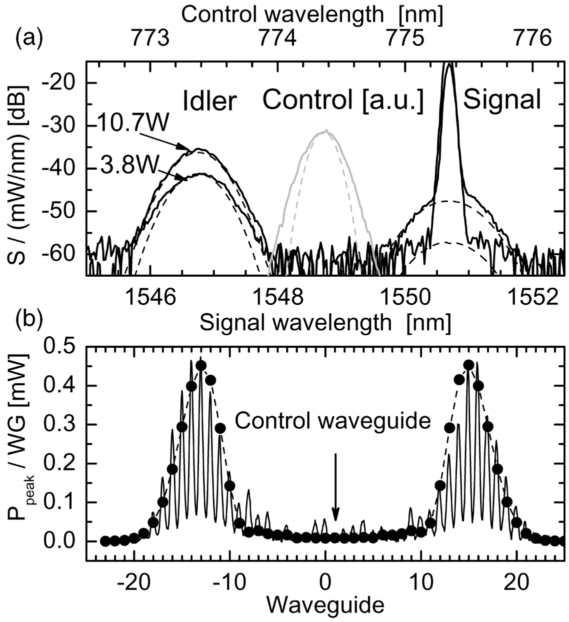

Fig. 3. (a) Output spectral density S from waveguide 15 for a control input with $P_{C\mathrm{peak}} = 3.8$, 10.7 W and $P_S =$ 19 mW. The control spectrum is also shown. (b) Peak power of the idler ($\lambda_I = 1546.7$ nm) at the output for $P_{C\mathrm{peak}} = 10.7$ W and $P_S = 19$ mW. Dashed curves and filled circles show theory. The beam geometry is the same as in Fig. 2.

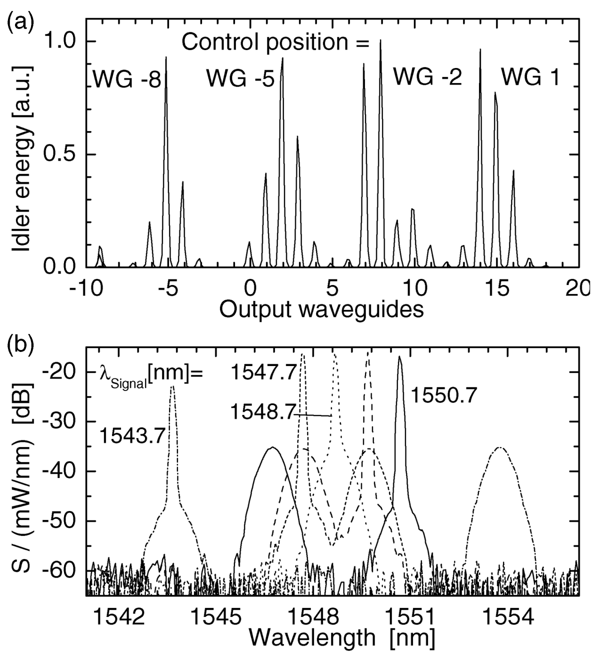

Fig. 4. (a) Spatial output distribution of the deflected idler for several positions of the control beam. (b) Spectral density of the deflected signal and idler in waveguide 15 for a number of signal wavelengths. $P_{C\mathrm{peak}} = 10.7$ W and $P_S = 19$ mW. The beam geometry is the same as in Fig. 2.

power of the injected control pulse (in the low-depletion limit) is also shown in Fig. 3(a). Because of the duty cycle of the control and the limited suppression of the spectral cross talk in the spectrum analyzer it was impossible to detect the parametrically amplified signal pulses and the idler with a cw detector near guide −13, where both of them spatially overlap the strong cw signal output beam. Hence we used a lock-in technique together with spectral filtering to measure the idler's output distribution, as shown in Fig. 3(b). For the maximum available control peak power of $P_{C\mathrm{peak}} = 10.7$ W in our experiment, a $P_S = 4$ mW cw input signal (power in the center waveguide of the beam) was converted to idler pulses with $P_{I\mathrm{peak}} = 0.45$ mW peak power (in the waveguide at the beam center). Simulations have shown that 38 W of control peak power would yield transparent switching with idler pulses also with 4-mW peak power. For higher control powers the device would provide parametric gain. All-optical control of the output position and wavelength was also verified. Figure 4(a) shows the spatial output distribution of the idler for four control input positions. Furthermore, simultaneous wavelength conversion to the idler with a bandwidth exceeding 10 nm is verified in Fig. 4(b).

The undistorted shape of the measured output spectra, together with detailed simulations of the parametric process as described in Ref. 7, confirmed the ultrafast switching capability of the device up to a data rate of 100 GHz. This limit is set mainly by the temporal walk-off between signal and control.

In conclusion, ultrafast, phase-insensitive all-optical spatial switching, amplification, and wavelength conversion were implemented in a single device. Routing of a milliwatt signal for four output channels with a simultaneous wavelength shift by as much as 10 nm was achieved.

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