High-speed transparent switch via frequency upconversion

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Abstract: We demonstrate a novel all-optical switch based on frequency upconversion. The switch features advantages for telecommunications: it is fast, transparent, frequency-multiplexable and bias-free.

OCIS codes: (190.4360) Nonlinear optics, devices; (230.4110) Modulators

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1. Introduction

The advent of telecommunication dense wave-division multiplexing systems (DWDM) that can transmit terabits per second has created a demand for optical switches capable of routing such optical signals. In order to fully harness the potential of high-speed optical networking, we require a switch which has low loss, low latency, transparency, and which can be easily frequency multiplexed to allow interoperation with DWDM systems. Here we show that optical switches based on frequency upconversion [1] can fulfill this demand. Upconversion-based switching[2, 3] may also have advantages over other types of switching such as electrooptic [4], cascaded non-linear [5], and Kerr cross-phase modulation [6].

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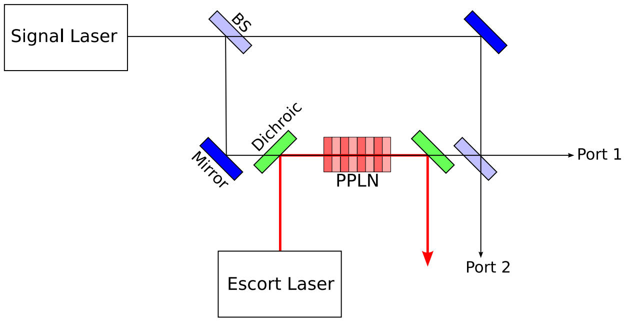

Fig. 1. Proposed design of a basic upconversion switch using a Mach-Zehnder interferometer. A Signal laser is sent though a balanced interferometer with a non-linear crystal (e.g., PPLN) in one arm. When an escort beam is passed through the crystal, co-linearly with the signal, a π-phase shift is applied to the signal, switching it from Port 1 to Port 2.

2. Theory of Upconversion

Frequency upconversion is a $\chi^{(2)}$ process which can convert an input laser beam to a different output frequency in the presence of a strong escort beam in a non-linear crystal. The input, escort, and output beams are respectively described by electric fields E_i, E_e, and E_o, angular frequencies ω_i, ω_e, and ω_o, and indices of refraction n_i, n_e, and n_o. Using the coupled wave equations for this $\chi^{(2)}$ non-linear process given by Myers et al. [7], and by satisfying conservation of energy ($\omega_i + \omega_e = \omega_o$) and conservation of momentum ($n_i\omega_i + n_e\omega_e + 2\pi c/\Lambda = n_o\omega_o$, where Λ is the poling period of our crystal), and assuming $E_e \gg E_i$, we can solve for the state as a function of position z in the crystal as the state converts from ω_i to ω_o:

$$|out\rangle = e^{i\phi_i}\cos(\alpha z)|\omega_i\rangle + e^{i(\phi_e+\phi_i+\pi/2)}\sin(\alpha z)|\omega_o\rangle, \tag{1}$$

where ϕ_i and ϕ_e are the input and escort phases, and α is a constant that depends on the experimental parameters. This is effectively a Rabi oscillation between the input and output frequencies, controlled by the strength of the escort field. If we choose the crystal length to be $L = \pi/\alpha$, then our final output state will be

$$|out\rangle = -e^{i\phi_i}|\omega_i\rangle, \tag{2}$$

which is equal to our original input state with a π-phase shift applied.

3. Mach-Zehnder Switch

Once we have the ability to apply π-phase shifts to our input beam, we may construct a switch by building an interferometer around the phase-modulator (Fig. 1). The input light enters a Mach-Zehnder interferometer, which has a non-linear crystal and an appropriately phase-matched escort beam in one arm. If the interferometer is balanced and no escort is applied, then all of the input light will exit Port 1. If the escort light is turned on, the input light will upconvert to the output frequency, then downconvert back to the input frequency, and acquire a π-phase shift. This will change the interference condition on the exit beam splitter and cause the light to leave the interferometer out of Port 2.

4. Polarization Switch

In practice, the previous design is somewhat difficult to implement in bulk materials since it is very sensitive to thermal drift of the crystal. While we require temperature stabilization

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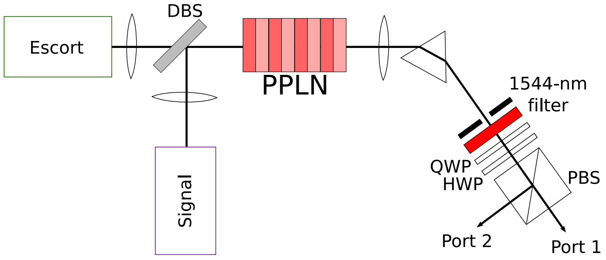

Fig. 2. Experimentally demonstrated polarization-based upconversion switch. A diagonally polarized signal is passed through a non-linear crystal phase-matched for upconversion with an escort laser. The signal is filtered, and then passed though two waveplates and a PBS so that it exits out Port 1. When the escort beam is turned on, a π-phase shift is applied to the vertical component of the signal, switching it from Port 1 to Port 2.

of the PPLN crystal to achieve phase-matching, this temperature tolerance is generally much greater than the temperature stability tolerance to require that the phase fluctuation due to the temperature-dependent index of refraction be much less than 2π. To partially alleviate this stability requirement, we implemented a different version of the switch, where instead of having two arms of a Mach-Zehnder interferometer, we used two polarizations of the same spatial mode (Fig. 2). Since both polarizations pass through the crystal–though only one polarization is upconverted–they both see a temperature-dependent index of refraction and the net phase is partially canceled out.

In our experiment we used a 1544-nm telecommunications laser diode [Agilent 81663A] to provide a signal beam with a peak power of $\sim$10 mW, which was focused inside of our crystal to a spot size of 70 μm. The signal was switched using a 1064-nm ND:YAG passively Q-switched escort laser with a repetition rate of 44 kHz, pulse width of 600 ps, and average power of 500 mW. The escort was focused onto a somewhat larger spot size of 250 μm. The increased size allows the signal to observe a relatively constant escort field over the width of the signal. We used a 4.5-cm Periodically Poled Lithium Niobate (PPLN) crystal with an 11.4-μm poling period as our non-linear medium. When heated to 70° C this crystal was quasi-phase matched for sum-frequency generation: 1544 nm + 1064 nm $\rightarrow$ 630 nm.

We combined our diagonally polarized signal with our vertically polarized escort on a dichroic beam splitter and passed both beams though the crystal. After the crystal a dispersion prism and a 1500-nm high-pass filter were used to separated the signal from the escort light. A quarter-wave plate (QWP) and half-wave plate (HWP) were used to negate the normal phase difference between the H and V polarization components of the signal traveling through the birefringent crystal, and to rotate the signal to horizontal polarization, which then passed though exit Port 1 of the polarizing beam splitter (PBS). During the escort pulse interval, the vertical component of the signal in the crystal acquires a π-phase shift, causing the crystal to act like an additional HWP. Now when the signal reaches the exit PBS it will be vertically polarized and will exit Port 2. We can measure the switching performance either by placing detectors in both ports of the PBS, or by using a detector on one port, and observing the output for two positions of the HWP separated by 45°. Using the latter technique, Fig. 3 shows the signals transmitted though each port during a switching cycle.

With this system we have achieved 20 dB of extinction in Port 2 and 12 dB of extinction in Port 1, with 0.7 dB of intrinsic switching loss in Port 2. The extinction ratio is mostly limited by spatial-mode mismatch, and therefore would be greatly improved by a waveguide implementation. The intrinsic switching loss is due to a failure of the the upconverted light to be converted

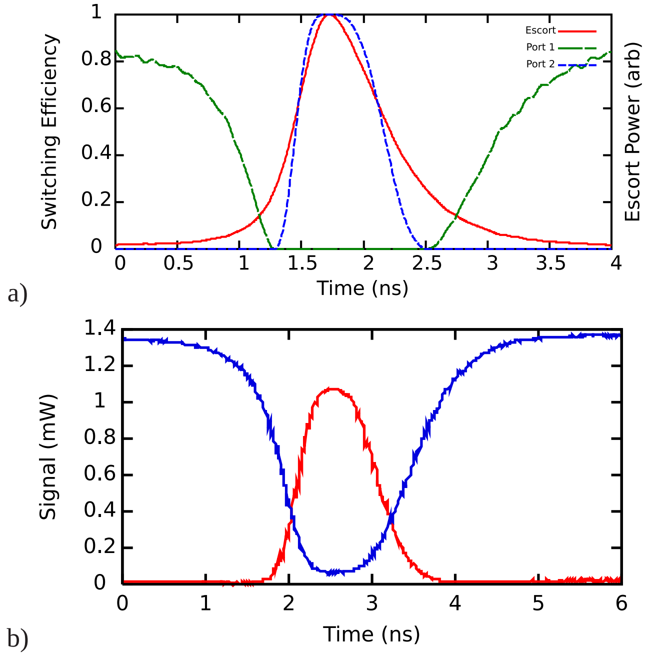

Fig. 3. a) Graph of temporal escort profile along with a model the unswitched and switched light calculated from the measured escort profile. Switched and unswitched does not sum to unity because some light is left in the upconverted 630-nm state. The width of the switched pulse light closely matches the escort width, however the unswitched light is broader since the unswitched light is completely depleted when the escort is at 25% of its peak power. b) Data collected from the polarization-based upconversion switch. A 1544-nm signal was modulated with a 600-ps wide 1064-nm pulse in 4.5-cm PPLN crystal. The blue trace is Port 1 and the red trace is Port 2. The extinction is 12 dB and ∼20 dB for Ports 1 and 2 and the intrinsic switching loss is about 30%. Each trace is a composite of 16 escort pulses to average out the noise on the photodetector.

back to the input wavelength. Together with an insertion loss from the other components (e.g., DBS, waveplates, filter, etc.) of about ∼15% , we achieve a total system transmission about about 70%.

The 200-ps switching time was limited by the Q-switched pulse width of the escort laser. By using a faster escort laser, much faster switching times should be realizable. The switching speed is also limited by the acceptance bandwidth of the crystal, however:

$$\Delta\lambda = \frac{2\lambda\Lambda}{\pi L}. \tag{3}$$

Faster switching requires shorter crystals, which in turn require higher escort intensities.

5. Frequency Multiplexing

After demonstrating fast and transparent switching, we also investigated the possibility of multiplexed switching. Since the π-phase shift is only applied to signals that are phase-matched to the switching escort beam, we are able to switch only a very narrow range of wavelengths while leaving the remaining wavelengths unaltered. This has applications in DWDM systems where it may be desirable to switch out a single frequency channel. To investigate this we used

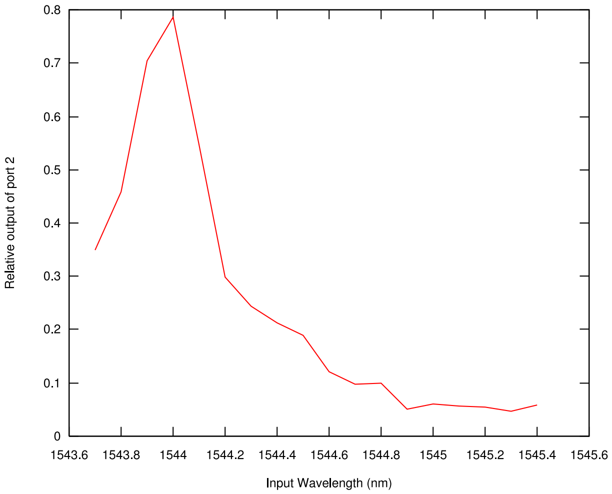

Fig. 4. Data showing the wavelength selectivity of the upconversion switch, which therefore allows for frequency multiplexing. The outputs of Port 1 and 2 are represented by the blue and red curves respectively. A 4.5-cm PPLN crystal and a 0.15-nm wide escort produce a 0.3-nm wide acceptance bandwidth. Nearby frequencies are unaltered. Transparency is limited to about 80% due to imperfect modematching between the escort and the signal. The excessive out-of-band output is due to the wide bandwidth of the passively Q-switched Nd:YAG escort laser used for conversion. Should this system be adapted for telecommunications applications, a narrow-band fiber-based escort laser would significantly reduce the out-of-band conversion efficiency, effectively suppressing the crosstalk in WDM configurations.

the setup described in Fig. 2, varied the input signal wavelength, and kept the escort wavelength constant. Our system was temperature-tuned for perfect quasi-phase-matching at 1544 nm, and we swept our input wavelength from 1543.7 nm to 1545.4 nm. We then measured the transmission of Port 2 as a function of wavelength and found a full width at half maximum (FWHM) switching bandwidth of 0.3 nm (Fig. 4). This can be controlled by varying the length of the crystal and the bandwidth of the escort beam. One can easily envision a more flexible and general switch: N independently controllable escort beams are used to control N different signal wavelengths. If the set of escort and signal wavelengths are spaced far enough apart so as not to phasematch with any other pair, activating some subset of the escort beams would switch only the corresponding set of signals, thus realizing a multi-frequency channel switch using only a single crystal.

6. Bias-Free Sagnac Switch

While the polarization-based switch has less temperature dependence than the Mach-Zehnder design, it is still susceptible to temperature stability requirements tighter that those required for phase-matching. For a 4.5-cm PPLN crystal, the Mach-Zehnder will vary 420° of phase per $^\circ$C, while the polarization design only varies 370° of phase per degree. Both of these designs, however, require biasing to compensate for the phase difference between the two paths (either two spatial modes or two polarizations). Biasing in the Mach-Zehnder design can be achieved by applying an electrically induced index change, either in the same arm as the PPLN or in a non-linear crystal placed in the opposite arm of the interferometer, similar to the way in which electrooptic switches are biased. With the polarization case, the biasing can be accomplished

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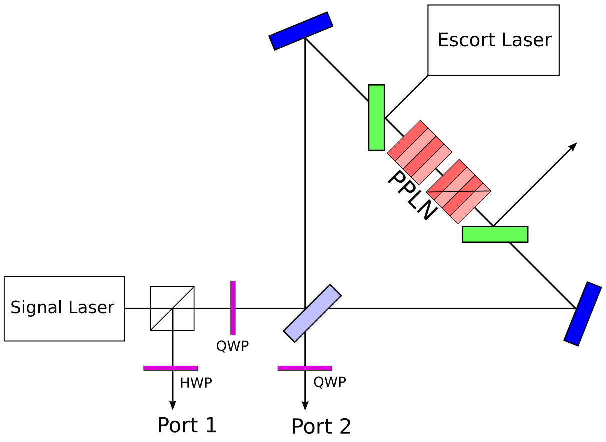

Fig. 5. Proposed design of a bias-free upconversion switch using a Sagnac design. Since only the signal co-propagating with the escort beam acquires a phase, modulating the escort beam will shift the interference of the interferometer at the beam splitter and control whether the signal exits at Port 1 or Port 2.

by setting the quarter- and half-wave plates to compensate for the extra phase difference caused by the birefringence of the crystal. In either case, switching performance requirements dictate that a dither-and-feedback circuit be used to hold a quadrature point, increasing complexity and limiting contrast.

We can eliminate this problem entirely by taking advantage of the fact that, unlike electrooptic switches, the phase is only applied to a beam which is co-propagating with the escort beam. A counter-propagating beam will not see a phase shift. This can be viewed as a weak time-reversal symmetry breaking (only the signal is time reversed), allowing us to implement a Sagnac design for the switch (Fig. 5).

A horizontally polarized signal is transmitted through a polarizing beam splitter and a QWP which rotates the signal into right-circular polarization. The signal is then split using a 50/50 beam splitter, so one half travels clockwise around the interferometer and the other half travels counter-clockwise. The escort applies a π-phase shift to the (co-propagating) clockwise beam, while the counter-clockwise beam is counter-propagating to the escort and therefore not affected. If the escort is off, the signal (now left-circular after having seen three reflections) exits the interferometer along the path which it came. The HWP rotates it to vertical polarization and it reflects off the PBS, passes through a HWP to become horizontally polarized again, and leaves the switch through Port 1. If the escort is on, the interference condition on the beam splitter is reversed, and the signal leaves though Port 2 after the final QWP rotates it back to horizontal polarization. To upconvert both the horizontal and vertical components of the circularly polarized light inside of the interferometer, we require two upconversion crystals with perpendicular optic axes, and a diagonally polarized escort. Since both paths (clockwise and counter-clockwise) have to pass though the same crystals with each polarization, there is no need for any bias control, since it is self-stabilizing: any index changed caused by temperature instability will identically affect both paths. This yields a bias-free switching configuration that only needs to be temperature stabilized to the level required for phase-matching.

For use in telecommunications systems, it is desirable to switch light in a polarization insensitive way, as most fiber optic networks use non-polarization preserving fibers. Polarization insensitivity can be achieved by splitting the signal into its horizontal and vertical components

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using a PBS, and then switching each polarization with an independent copy of the Sagnac switch. Since the switch itself is polarization preserving, we may recombine the outputs from the two interferometers using a PBS at each port, realizing a fully polarization independent switch. This can be made efficient by reusing the two most expensive resources: the nonlinear crystal and the escort laser. We can use the same PPLN crystals for both copies of the interferometer by implanting two parallel waveguide channels in the crystal, one for each interferometer. Also, since the escort is not depleted during the upconversion process, we may direct it through both channels in series by appropriate configuration of the dichroic beamsplitters, thereby enabling a single escort to operate both switches without requiring additional power.

7. Conclusion

By utilizing frequency upconversion we have demonstrated fast, transparent, efficient, multiplexable, bias-free optical switching suitable for classical and quantum communications. While we have focused on $\chi^{(2)}$ non-linear processes, the techniques could be generalized to $\chi^{(3)}$-based upconversion systems. Where high efficiency upconversion is possible [8, 9], the concomitant π-phase shift necessary for switching can be obtained. This technique can also be used in waveguide-based integrated optical systems, where the decreased mode volume of the waveguide would dramatically lower the requirements for escort power [10].

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