

Experimental demonstration of 1535–1555-nm simultaneous optical wavelength interchange with a nonlinear photonic crystal

Aref Chowdhury,* Chad Staus, and Brian F. Boland

Department of Electrical and Computer Engineering, University of Wisconsin—Madison, Madison, Wisconsin 53706

Thomas F. Kuech

Department of Chemical Engineering, University of Wisconsin—Madison, Madison, Wisconsin 53706

Leon McCaughan

Department of Electrical and Computer Engineering, University of Wisconsin—Madison, Madison, Wisconsin 53706

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We present results of what is to our knowledge the first experimental demonstration of simultaneous optical wavelength interchange by use of a two-dimensional second-order nonlinear photonic crystal. Fabrication and performance parameters of a 1535–1555-nm wavelength interchange nonlinear photonic crystal fabricated in lithium niobate are discussed. © 2001 Optical Society of America

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Nonlinear photonic crystals (NLPCs) have been an area of increasing research interest in the past few years, especially because of their unique spatio-spectral characteristics that enable them to perform a variety of all-optical functions. Since Berger's seminal paper on NLPCs in 1998,¹ second-harmonic generation in hexagonally poled LiNbO₃ has been experimentally demonstrated² and analyses of multiple-harmonic generation made.^{3,4} To our knowledge, the first telecommunication application of NLPCs was the theoretical demonstration of simultaneous optical wavelength interchange.⁵ In that Letter it was shown that a two-dimensional quadratic nonlinear photonic crystal provides a mechanism for a selective one-step optical carrier interchange process in which the data from each wavelength of a pair are swapped with those of the other wavelength; these converted signals are simultaneously spatially segregated from the unconverted ones, thus eliminating coherent in-band cross talk.

In this Letter we present what we believe is the first experimental demonstration of simultaneous optical wavelength interchange. The nonlinear lattice, fabricated in LiNbO₃, was designed to interchange the wavelengths 1535 and 1555 nm. The wavelength interchange process takes place by means of two concurrent difference-frequency generation processes: The two difference-frequency processes in effect diffract the converted signals from the unconverted ones, as depicted in Fig. 1. We also present details of the fabrication and characterization of the NLPC.

For the output specifications of the device, we decided that the 1555 → 1535 nm output would exit at +5° and that the 1535 → 1555 nm output would exit at

−7° to the direction of propagation of the input waves. Given these output specifications, we used the general nonlinear Bragg condition, $\sin(\phi)$ relation, and Eq. (8) of Ref. 5 to derive the real space parameters. The real space lattice consisted of basis vectors $\mathbf{a} = 7.6 \mu\text{m}$ and $\mathbf{b} = 10.1 \mu\text{m}$, with an interior angle of 47.1°, as shown in Fig. 2. The required direction of propagation of the input pump and signals with respect to the lattice is also shown in Fig. 2. The unit cell was chosen to be a 4.4- μm -diameter solid circle, which translates to a unit cell fill factor of ~27%.

The two-dimensional NLPC was patterned by standard photolithography on the +z face of a 0.5-mm LiNbO₃ wafer. The 3- μm -thick photoresist pattern was poled with an electric field of ~22 kV/mm. Figure 3 is an optical micrograph of a well-defined lattice region of the unetched poled pattern; not all the sample exhibited such uniformity in poling, as is

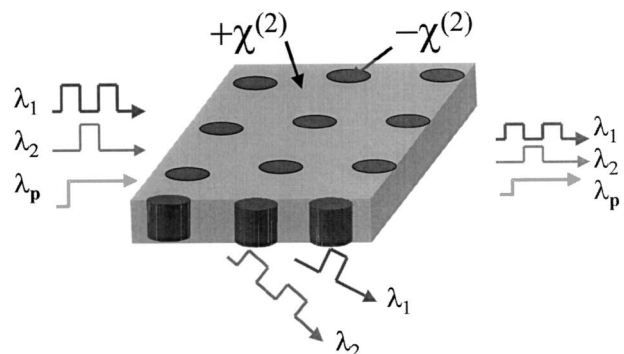


Fig. 1. Schematic representation of simultaneous optical wavelength interchange.

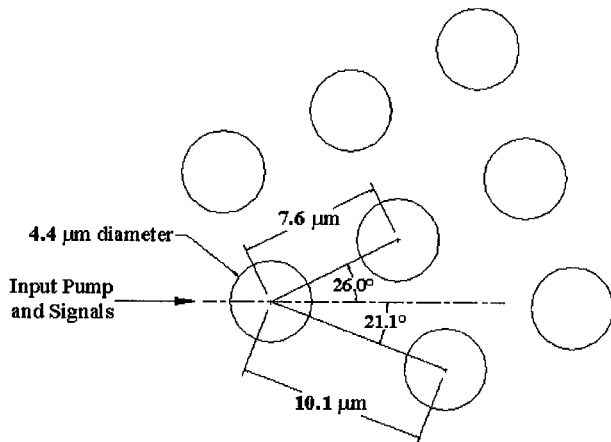


Fig. 2. Real-space parameters of the 1535–1555-nm wavelength interchange nonlinear photonic crystal. The direction of propagation of the collinear multiplexed input pump and signals is shown with respect to the lattice.

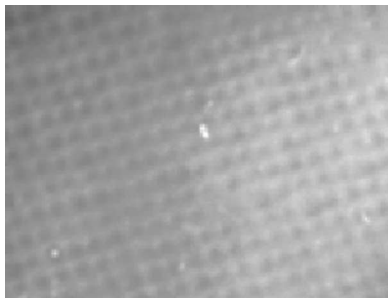


Fig. 3. Optical micrograph of a well-defined lattice region of the unetched poled pattern.

shown in Fig. 4. The unetched sample reveals the lattice points under an optical microscope that are likely due to the strain-induced change in refractive index that results from the poling process.⁶ To enable larger areas to be viewed more easily and for better contrast, we etched the poled pattern with a 1:4 mixture of HF:HNO₃ at room temperature for ~5 min. Figure 4 shows the etched sample under a lower magnification. As can be seen from the figure, there are large patches of overpoled regions. The overpoled regions are a result of the lateral growth of the domains^{7,8} under the photoresist.

An optical diffraction pattern of the etched crystal was taken with a He–Ne laser aligned nearly perpendicularly to the LiNbO₃ +z face (Fig. 5). The resultant diffraction pattern represents the reciprocal lattice of the periodically poled pattern and is an indication of the quality of the nonlinear crystal. The diffraction angles were found to be consistent with the real space periodicities. We note that we have achieved substantially smaller two-dimensional periodicities (7.6 and 10.1 μm) than had previously been obtained by others.² The crystal was subsequently cut and polished, resulting in a sample with dimensions 11 mm × 6 mm.

The interchange experiment involved illuminating the sample with three collinear continuous-wave optical sources: a 772.5-nm pump from a Ti:Al₂O₃ laser and two distributed-feedback diode laser sources

nominally at 1535 and 1555 nm. The output from the Ti:Al₂O₃ laser was ~0.75 W; the two distributed-feedback laser sources were amplified with an Er-doped fiber amplifier to ~1 W each. The input collinear beams had a waist diameter of ~1 mm located at the exit face of the crystal. The LiNbO₃ nonlinear photonic crystal was maintained at ~200 °C to mitigate the photorefractive effect. After Fresnel losses were accounted for, the power entering the crystal was ~325 mW at 772.5 nm and ~500 mW at each of the signal wavelengths. Figure 6 shows the output spectra for the exit angles +5° and –7°. At the +5° angle we see the expected interchanged output signal of 1555 → 1535-nm and no 1555-nm signal; similarly, at the –7° exit angle we see the 1535 → 1555-nm output with no light at 1535 nm. To confirm the

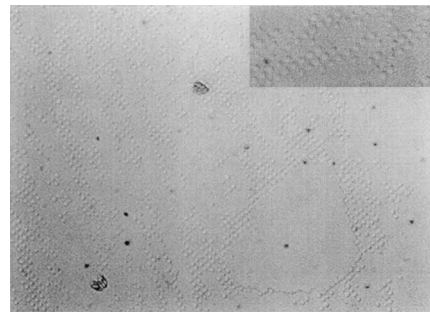


Fig. 4. Optical micrographs of the etched two-dimensional poled nonlinear photonic crystal.



Fig. 5. Optical diffraction pattern of the two-dimensional poled nonlinear photonic crystal.

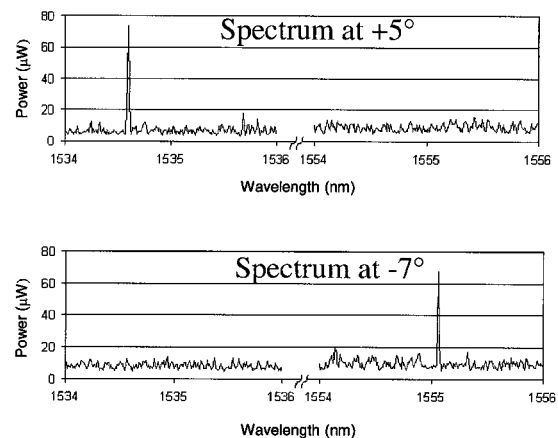


Fig. 6. Interchanged spectra taken at +5° and –7°.

interchange process, we extinguished each of the distributed-feedback inputs individually (1535 and 1555 nm) and observed that the corresponding output signal wavelength was also eliminated (1555 and 1535 nm, respectively). The linewidths of the spectra in Fig. 6 appear broader than they are in reality because the resolution was spectrometer limited to ~ 0.02 nm. The output power at the interchanged wavelength 1535 nm was ~ 75 μ W and at 1555 nm was ~ 65 μ W. The output power at 1535 nm was expected to be larger than that at 1555 nm because of its smaller exit angle, corresponding to a longer spatial overlap factor for the interacting waves, which resulted in a higher efficiency.

In summary, we have performed what we believe is the first experimental demonstration of simultaneous optical wavelength interchange by use of a two-dimensional nonlinear photonic crystal. This optical function is to our knowledge also the first telecommunication application of nonlinear photonic crystals proposed or demonstrated. The conversion efficiency is expected to increase with improved periodically poled patterns. We note that improvements such as thicker photoresist and a modified poling waveform will likely produce a more nearly uniformly poled pattern over a larger area because these approaches have the potential to reduce the lateral growth of domains.

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*Present address, Optical Physics Research Department, Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey, 07974.

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