Two-spatial-mode parametric amplifier in lithium niobate waveguides with asymmetric Y junctions

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For optical parametric amplifiers in proton-exchange waveguide devices reported to date, both the signal and the idler photons are in the TM_{00} mode, causing difficulty in distinguishing signal from idler. We report a two-mode optical parametric amplifier. The key components, asymmetric Y junctions, successfully launch the pump wave in a pure TM_{10} mode and separate the signal and the idler in the TM_{10} and TM_{00} modes with a power ratio of as much as 27.5 dB. With high parametric gain, optical parametric generation with a threshold of 300 pJ/pulse was demonstrated for 1.8 ps long pump pulses near 780 nm. These periodically poled lithium niobate waveguides are efficient integrable photon sources. © 2006 Optical Society of America

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Optical parametric amplifiers are important sources of tunable ultrashort infrared pulses and are also useful photon sources.[1,2] Channel waveguides can be used to enhance the intensities of the interacting waves over long interaction lengths, decreasing the required pump power. The most efficient waveguides in lithium niobate reported to date are based on reverse proton exchange, in which the threshold for optical parametric generation (OPG) reached 200 pJ for 1.8 ps long pump pulses near 780 nm.[3] However, separating the photons of different wavelengths generated in these waveguides is difficult, especially near degeneracy. Inside the waveguides all the waves are propagating in the same direction and cannot be separated by angular selection. Outside the waveguides prisms or filters work only for wavelengths away from degeneracy and are difficult to integrate; polarization techniques fail because only TM modes are guided. In this Letter we demonstrate that mode demultiplexing with asymmetric Y junctions is a good approach to separating the signal from the idler for parametric amplifications in proton-exchange lithium niobate waveguides.

Mode demultiplexing with asymmetric Y junctions is based on the adiabatic variation of the refractive-index distribution along the device. Depending on which end the waves are launched from, asymmetric Y junctions are efficient mode multiplexers or demultiplexers within a wavelength span.[4,5] For waves near 1550 nm, a power contrast of >30 dB between the TM_{00} and the TM_{10} modes had been demonstrated.[5] To achieve mode demultiplexing in OPG we use an asymmetric Y junction as a mode multiplexer for the pump and as a mode demultiplexer for the signal and the idler.

Figure 1 shows the design of such a device and illustrates how the modes of the interacting waves evolve along it. On the input side, the TEM_{00} input pump beam launched into the narrow arm of the mode multiplexer is converted into the TM_{10} waveguide mode. Then the pump propagates through the quasi-phase-matching region and generates signal and idler in two spatial modes (the TM_{10} mode and the TM_{00} mode).[5,6] On the output side, signal and idler waves in different modes will emerge from different arms of the mode demultiplexer. The widths of the two arms of the asymmetric Y junctions are 2 μm (3 μm) on the input side and 3 μm (5 μm) on the output side, designed for the pump near 780 nm and the signal (idler) near 1560 nm to produce the best mode contrast between the TM_{00} and the TM_{10} modes.[7] In this Letter we define the OPG product with shorter (longer) wavelength as the signal (idler), and waveguide width is defined as the mask opening for proton exchange.

In the OPG experiments the chips were heated to 130 °C. The quasi-phase-matching periods of the gratings were 16.45 μm. The devices were fabricated with our typical procedure.[8] The FWHM of the pump pulses was 1.8 ps. For different purposes we chose various waveguide widths from 8 to 14 μm in the interaction region and designed devices with or without the mode demultiplexer for the signal and the idler.

Without the mode demultiplexer we can obtain the mode contrast out of the mode multiplexer by monitoring the mode shape of the transmitted pump. Almost pure TM_{00} or TM_{10} modes were obtained when we launched a cw near 780 nm in the TEM_{00} mode from the wide or narrow arm of the mode multiplexer for the pump. For a wave converted into an almost pure TM_{10} mode, we can tune the wavelength to find the highest contrast between the peak intensities of the two lobes recorded on a camera and thus deduce the contrast between the different mode contents. The highest mode contrast measured was >30 dB.

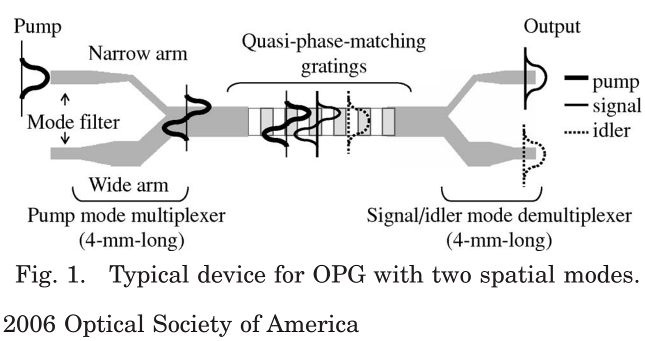

Fig. 1. Typical device for OPG with two spatial modes.

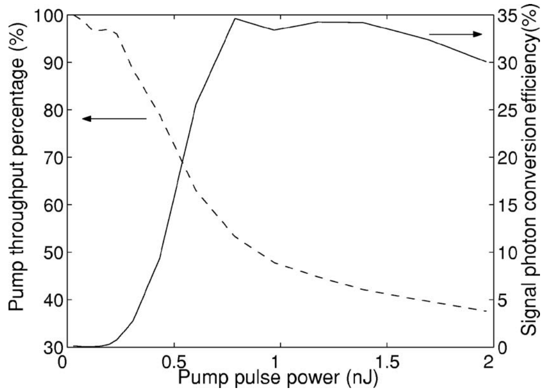

Fig. 2. Threshold measurement for OPG with the pump in the TM_{10} mode.

Figure 2 shows the curves of photon conversion and pump throughput for OPG with the pump in pure TM_{10} mode. For a fair comparison with former results,[3] we note that the length of the quasi-phase-matching gratings was 42 mm and that cascaded OPG processes were absent. With the pump at 785.7 nm, the OPG threshold was $\sim$300 pJ, which is defined as that point when the parametric gain $G \sim \exp(2\sqrt{\eta P}L)$ reaches 100 dB. Here P is the pump power, L is the length of the gratings, and η is the normalized gain parameter in optical parametric amplification, which near degeneracy is equal to that of second-harmonic generation. We deduced that $\eta \sim 60\%/(\mathrm{W\ cm}^2)$ with the pump in the TM_{10} mode, compared with a threshold of 200 pJ and $\eta \sim 90\%/(\mathrm{W\ cm}^2)$ with all the waves in the TM_{00} mode.[3] The maximum photon conversion efficiency reached 35% for a pump power of 780 pJ/pulse.

The power spectra and wavelength-tuning curves with the pump in the TM_{10} mode are more complex than those that involve only TM_{00} modes because two near-degenerate processes exist in this regime. With either the signal or the idler in the TM_{10} mode while the other is in the TM_{00} mode, these two processes split because the waveguide dispersions of the two modes are different. However, they are distinguishable by use of asymmetric Y junctions.

Before examining this behavior, we measured the mode separation ability of an asymmetric Y junction by recording the power spectra of the signal that emerged from its two arms. In Fig. 3(a), all the waves involved were in the TM_{00} mode. In Fig. 3(b) the pump was in the TM_{10} mode, the signal near 1375 nm was in the TM_{10} mode, and the idler near 1843 nm was in the TM_{00} mode. The solid (dotted) curves are the power spectra of the signal out of the wide (narrow) arm of a mode demultiplexer; their power ratio thus gives the mode separation ability of the asymmetric Y junction, which is 27.5 dB in both cases.

With such good mode demultiplexers, we measured the signal power spectra for the two near-degenerate processes in a 14 μm wide waveguide with the pump in the TM_{10} mode. In Fig. 4 the solid curve corresponds to the signal in the TM_{00} mode, whereas the dotted curve corresponds to that in the TM_{10} mode. The idler in both cases is near 1.9 μm and is not shown. Simulations gave a ratio of 0.7 between normalized gain parameter η for the two cases. Parametric gain G is $\sim$100 dB near the OPG threshold; values of G for the two cases would therefore differ by $\sim$16 dB, matching well the 12 dB value measured.

This difference in parametric gain depends on the waveguide width and the wavelengths of the interaction. For an 8 μm wide waveguide on a different chip, this difference decreased to 5 dB when the wavelength of the pump was tuned to 784.4 nm to bring the signal and the idler to near degeneracy. Figure 5 shows the broadband signal and idler near degeneracy out of the two arms of a mode demultiplexer. The solid (dotted) curve corresponds to the OPG product in the $TM_{00}(TM_{10})$ mode. The mode separation ability of the asymmetric Y junctions was >20 dB from 1450 to 1700 nm. The sharp peaks near 1465 and 1689 nm are from cascaded OPG,[3] which would be absent in the low-gain regime if the devices were used as photon-pair sources. Other than these peaks, the curves have two pairs of peaks: 1485 and 1662 nm, and 1538 and 1600 nm, corresponding to

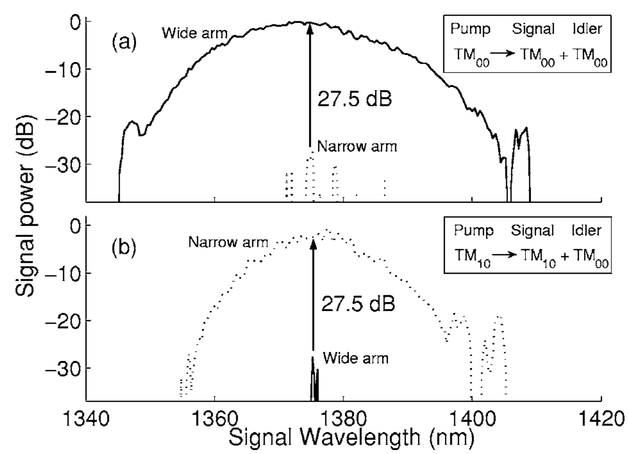

Fig. 3. Power spectra of the OPG signal for the processes shown in the insets. The solid (dotted) curves show the signal emerging from the wide (narrow) arm of a mode demultiplexer. The idler near 1843 nm was not recorded.

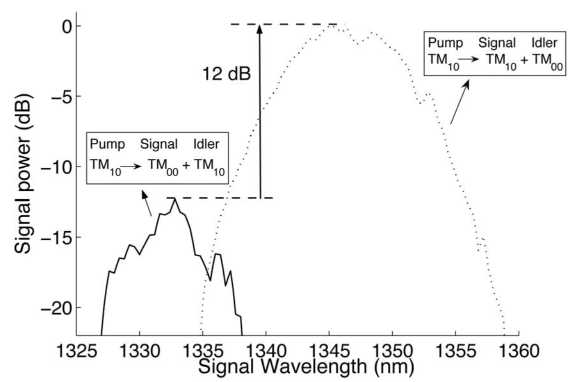

Fig. 4. Power spectra of the OPG signal from the two near-degenerate processes with the pump in the TM_{10} mode. The solid curve centered at 1332 nm shows the signal in the TM_{00} mode (with the idler centered at 1908 nm in the TM_{10} mode); the dotted curve centered at 1346 nm shows the signal in the TM_{10} mode (with the idler centered at 1880 nm in the TM_{00} mode).

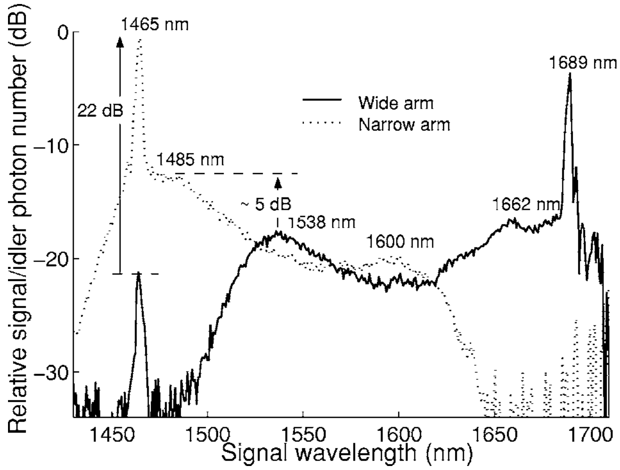

Fig. 5. Spectra of the OPG products near degeneracy with the pump in the TM_{10} mode. The solid (dotted) curve shows the output from the wide (narrow) arm of a mode demultiplexer.

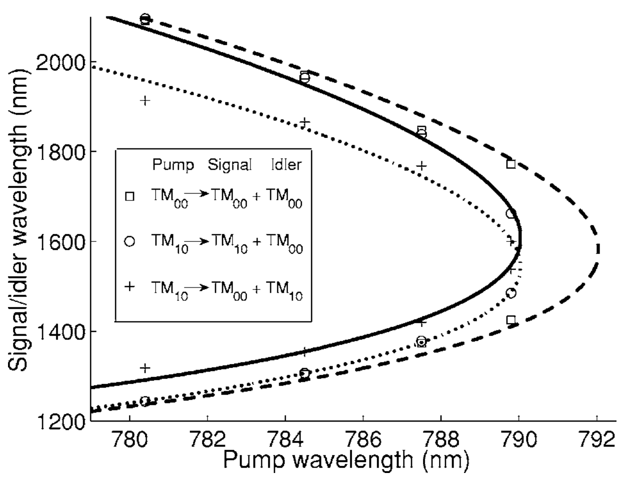

Fig. 6. Wavelength-tuning curves for OPG in a 9.5 μm wide waveguide. The curves show simulations. The dashed curve corresponds to OPG involving only TM_{00} modes. The solid (dotted) curve corresponds to the OPG products in the TM_{00}(TM_{10}) mode with the pump wave in the TM_{10} mode. The symbols illustrate measurements and correspond to the three processes shown in the inset.

the center wavelengths of signal and idler from the two near-degenerate processes. Because of the split of the two processes, the total bandwidth is wider than it would be if only one process existed.

The wavelength-tuning curves for various OPG processes in a 9.5 μm wide waveguide were deduced from the power spectra obtained at different pump wavelengths. In Fig. 6 the curves show values from simulations; the symbols, from measurements. The dashed curve corresponds to OPG with all the waves in the TM_{00} mode. The solid (dotted) curve corresponds to the OPG products in the TM_{00}(TM_{10}) mode with the pump in the TM_{10} mode. The symbols correspond to the OPG processes shown in the inset. Unlike in OPG involving only TM_{00} modes, in general two pairs of signal–idler exist at every pump wavelength when the pump is in the TM_{10} mode. Moreover, instead of ending at degeneracy, the possible pump wavelength for OPG extends to the point where the group velocities of the signal (in the TM_{10} mode) and the idler (in the TM_{00} mode) match, at the extreme points of both the solid and dotted curves in Fig. 6.

In summary, our waveguide devices with asymmetric Y junctions are highly effective in mode demultiplexing for optical parametric amplification. The threshold for OPG with the pump in the TM_{10} mode was as low as 300 pJ, and the maximum photon conversion efficiency reached 35%. The mode contrast out of the mode multiplexer designed for a pump wavelength near 780 nm reached 30 dB, and the mode separation ability of the mode demultiplexer designed for the signal and the idler reached 27.5 dB. We have therefore illustrated a new approach to generating and separating signal and idler waves for compact and efficient tunable light or photon-pair sources.

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