Mode multiplexing in optical frequency mixers

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Asymmetric Y junctions allow the development of a new class of optical frequency mixers that utilize higher-order waveguide modes for signal processing. We measure high-contrast (>30 dB) mode sorting in asymmetric Y junctions by use of a novel technique: efficient TM$_{00}$, TM$_{10}$, and TM$_{20}$ mode mixing in a periodically poled lithium niobate waveguide. We also demonstrate an odd-to-even mode wavelength converter capable of spectral inversion without offset or bidirectional wavelength conversion. © 2004 Optical Society of America

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Optical frequency (OF) mixers based on periodically poled lithium niobate (PPLN) waveguides have been used to demonstrate many useful all-optical signal processing functions, including wavelength conversion,[1] dispersion compensation by spectral inversion,[2] and 160-Gbits/s optical time-division multiplexing.[3] Mode multiplexing extends the functionality of OF mixers even further. In particular, higher-order waveguide modes offer an important new way to distinguish and spatially separate the output of a nonlinear mixer from the residual input. We show that mode sorters based on asymmetric Y junctions are suitable for mode multiplexing in OF mixers and demonstrate a proof-of-principle odd-to-even mode wavelength converter with separate output ports for the mixer output and the residual input.

In a standard waveguide OF mixer, all the interacting waves propagate in the (lowest-order) 00 mode [Fig. 1(a)]. Mixing in a quasi-phase-matching (QPM) grating section produces a wavelength-converted output E_3 that can be separated from the pump and residual inputs (E_1 and E_2) by spectral filtering. In bidirectional wavelength conversion or spectral inversion without offset, however, the input and output contain the same wavelengths, making them impossible to distinguish, let alone separate spatially. With a polarizing beam splitter rather than a filter in Fig. 1(a) a type II phase-matching scheme can solve this problem when two polarizations are available. Unfortunately, well-developed systems such as proton-exchanged waveguides in lithium niobate support only TM modes, and type II phase matching uses smaller nonlinear coefficients than QPM with the diagonal d_{33} coefficient. Two other possibilities for separating degenerate input and output wavelengths in PPLN OF mixers include an OF balanced mixer based on interferometer structures[4] and a two-stage wavelength conversion scheme with intermediate filtering.[5] Both approaches add considerable complexity and can be difficult to implement. An elegant alternative is to use higher-order waveguide modes to distinguish and spatially separate the interacting waves. As shown in Fig. 1(b), 00-mode input waves (E_1 and E_2) can mix to produce a 10-mode output wave E_3; the efficiency of odd–even mode mixing can be greatly enhanced with asymmetric QPM gratings.[6] The mixer output can then be separated from the residual input by filtering the two modes with an integrated optics structure such as an asymmetric Y junction.

The mode-converting properties of asymmetric Y junctions have been known for decades[7] and have recently been used in high-contrast switches.[8,9] Launching into the narrow odd port of an asymmetric Y junction converts a 00-mode into a 10-mode, whereas launching into the wider even port leaves the mode unchanged (Fig. 2). Viewed in the opposite propagation direction, the junction sorts 00-modes and 10-modes. This sorting behavior occurs when the branches separate gradually enough that their modes evolve adiabatically, remaining local normal modes throughout the structure. The smooth refractive-index profiles of annealed proton exchange waveguides make it relatively easy to fabricate adiabatic asymmetric Y junctions that sort TM$_{00}$ and TM$_{10}$ modes with greater than 30 dB of contrast. The junctions maintain this high contrast across the 1550-nm band without adding measurable propagation losses. Current junction designs are based on two unequal waveguides whose edge-to-edge separation decreases linearly from 20 μm to zero. In a typical design the waveguide widths are 5 and 3 μm (the latter being nearly cut off), and the junction occurs over 3–4 mm. Although these designs are still being optimized with local-normal mode calculations and beam propagation method simulations, they are already short enough to be integrated with PPLN OF mixers, which can be 60-mm-long for 3-in. (76 mm) lithium niobate wafers.

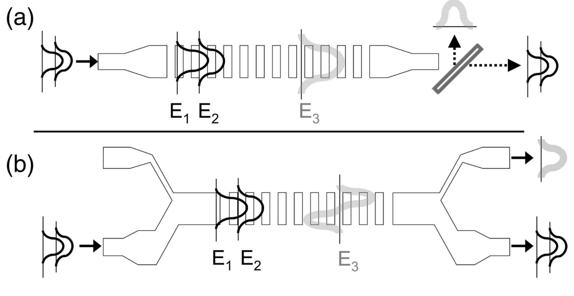

Fig. 1. (a) Conventional QPM waveguide mixing and filtering versus (b) odd–even mode mixing and sorting.

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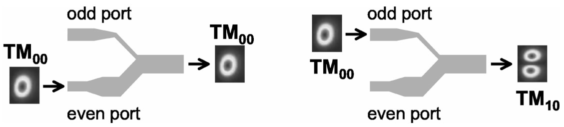

Fig. 2. Mode-sorting behavior in an asymmetric Y junction. The modes of the larger and smaller input branches evolve into the first and second modes of the combined junction.

One challenge faced in characterizing asymmetric Y-junction designs is measuring mode content (TM_{00} versus TM_{10}) with a resolution better than 0.1%. Imaging the modal interference at the waveguide output may not provide such precise information without some knowledge of the mode shapes or their relative phase. We have developed a simple but sensitive technique for measuring waveguide mode content at the first-harmonic (FH) wavelength by use of QPM nonlinear mixing between the modes, which we label FH_{00} and FH_{10}. With these two modes, three different processes of second-harmonic (SH) generation (SHG) and sum-frequency generation (SFG) are possible:

$$SH_{00} = \eta_{00}(FH_{00})^2, \qquad SH_{10} = 4\eta_{10}FH_{00}FH_{10},$$
$$SH_{20} = \eta_{20}(FH_{10})^2. \tag{1}$$

These equations relate SH and FH mode power and the conversion efficiency of each process. The efficiency ratio of $\eta_{20}{:}\eta_{00}{:}4\eta_{10}$, obtained by both calculation and experiment, is 0.22:0.43:1.00, where unity corresponds to $120\%/\mathrm{W/cm}^2$. Dividing the first or third equations by the second, we see that measuring the relative SH power produced by each process in the same device yields a direct, linear measurement of the ratio of FH_{00}/FH_{10}. Choosing three different SH output modes has several advantages: It makes the processes easily distinguishable, it allows the use of standard (as opposed to asymmetric) QPM gratings,[6] and it results in similar QPM periods for all three interactions.

Figure 3 shows the measured (open symbols) and calculated (thicker curve) phase-matching wavelengths for all three processes for five different waveguide widths and the same QPM period (15.15 μm). Our waveguide fabrication model[10] successfully predicts the absolute phase-matching wavelength as well as the shapes of these curves. The 17-μm width is convenient for mode content measurements because it yields three distinct SHG tuning curves within a span of only 5 nm, which is short enough to ensure constant coupling and power levels from a tunable diode laser. In a series of devices similar to those in Ref. 6, various asymmetric Y-junction designs were tested by launching 1 mW of FH power through the odd and even input ports into a 40-mm-long mixing section and measuring the SH output. The gray and black tuning curves in Fig. 4, which correspond to odd and even port launching, contain SH_{20}, SH_{00}, and SH_{10} peaks at roughly 1542, 1543, and 1545 nm due to a 15.0-μm QPM period. Relatively large SH_{20} and SH_{00} peaks indicate high-purity FH_{10} and FH_{00} mode launching, whereas a relatively large SH_{10} peak corresponds to a more equal mixture of FH modes and therefore a lower-contrast junction.

Figure 4(a) reveals FH_{00}/FH_{10} ratios of 11 dB and (negative) 10 dB for even and odd port launching, respectively, in a typical, first-generation device. This contrast was vastly improved [Fig. 4(b)] by stretching out the design by a factor of 5 to make the junction more adiabatic. As seen in the enlarged scale in Fig. 4(c), the SH_{10} peak at 1545 nm is nearly lost in the wings of the other SH peaks, corresponding to a contrast of at least 27 and 32 dB for the even and odd ports, respectively. Note that the peak spacing, and thus the dynamic range of this technique, could be readily increased by changing the waveguide design. Symmetric Y-junction measurements [Fig. 4(d)] show, as expected, that both ports launch an equal mode mixture ($FH_{00}/FH_{10} = 1$); they also provide an independent check on the SH efficiency calibration (superimposed square symbols). Interestingly, the 1541-nm

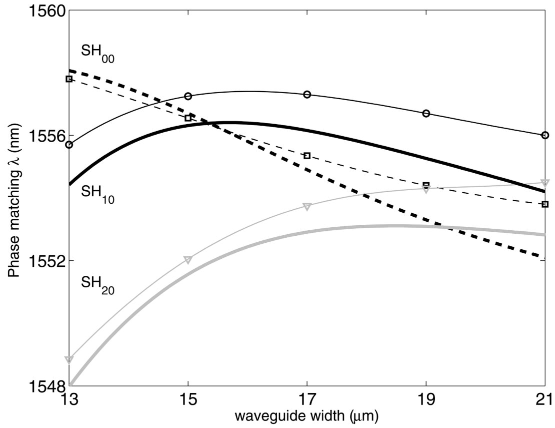

Fig. 3. Measured (open symbols) and calculated (thicker curve) phase-matching wavelengths versus waveguide width for all three SHG and SFG processes; the QPM period is fixed at 15.15 μm.

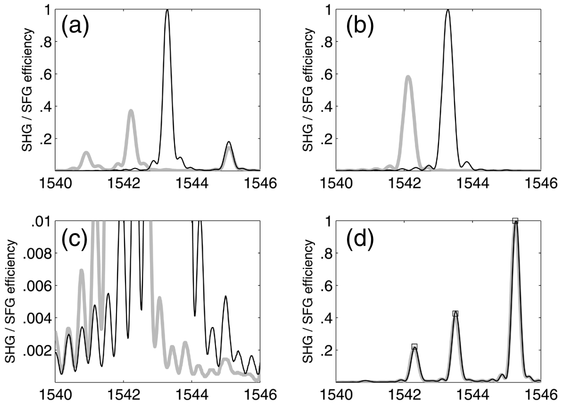

Fig. 4. SHG and SFG tuning curves for odd (gray) and even (black) port launching into an odd–even mode OF mixer. (a) The 1545-nm peak indicates a FH_{00} and FH_{10} mode mixture and a low-contrast asymmetric Y junction. (b) By use of a high-contrast junction, this peak is reduced and (c) can be seen only by magnifying the abscissa. (d) The relative peak heights for a symmetric Y junction confirm an equal FH_{00} and FH_{10} mode mixture for both ports.

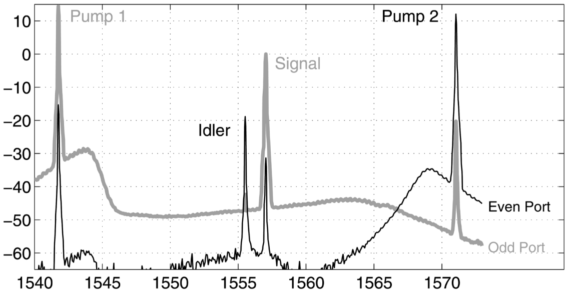

Fig. 5. Measured output power versus wavelength for an odd–even mode wavelength converter. The odd port (gray) contains most of the residual signal (1557.0 nm), whereas the even port (black) contains 12.5 dB more mixer output (1555.8 nm) than residual signal. Transmission of the residual pumps shows the full device contrast to be greater than 30 dB.

peak in Fig. 4(a) corresponds to yet another mixing process, $SH_{40} = \eta_{40}(FH_{20})^2$.

Using provisional asymmetric Y-junction designs, we fabricated and tested the odd–even mode OF mixer in Fig. 1(b). A 1-mW signal at 1557.0 nm launched through the odd input port into a FH_{10} mode produces a wavelength-converted FH_{00}-mode output at 1555.5 nm by cascaded $\chi^{(2)}$ mixing.[11] Because of the second junction, the even output port contains most of this mixer output (the idler wave), whereas the odd output port contains most of the residual input signal; the black and gray traces in Fig. 5 show the optical spectrum measured at both ports. In this proof-of-principle device the conversion efficiency was only −18.8 dB because of shortened QPM gratings, and consequently the even port contrast between the mixer output and the residual input was reduced to 12.5 dB. With standard length gratings, however, the conversion efficiency would be roughly 0 dB given the pump power used in this experiment (~100 mW at both ports), and the contrast would reach 30 dB, which is sufficient for optical signal processing applications. Unlike the standard cascaded OF mixer, the current device uses odd–even mode SFG rather than 00-mode SHG to produce the SH wavelength needed for difference-frequency mixing. As shown in Fig. 5, this choice reserves the center of the conversion band for spectral inversion without offset. The pumps are launched simultaneously, one into each input port, using a V-groove fiber array. Matching the 250-μm array spacing to the 20-μm asymmetric Y-junction separation requires 3-mm-long S-bend sections in the annealed proton exchange waveguides.

In conclusion, we have used asymmetric Y junctions as a tool for mode control in OF mixers, using them to demonstrate high-contrast (>30 dB) mode sorting in an odd-to-even mode wavelength converter. With higher efficiency or more pump power, this device would allow practical bidirectional wavelength conversion or spectral inversion without offset. In future work, the same scheme could be applied in optical parametric generators or oscillators to separate or manipulate the signal and idler waves. Expanding the use of asymmetric Y junctions to a larger set of higher-order modes (while maintaining a geometry with 00-mode inputs and outputs) will allow mode multiplexing to complement time-division and wavelength-division multiplexing techniques.

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