Odd waveguide mode quasi-phase matching with angled and staggered gratings

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Angled and staggered gratings are used for quasi-phase matching of antisymmetric TM_{10} modes in periodically poled lithium niobate waveguides with high efficiency. Control of the symmetry of the nonlinear coefficient d adds a new degree of freedom in the choice of which waveguide modes will interact in a quasi-phase-matched device. © 2002 Optical Society of America

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Distinguishing and spatially separating the interacting waves in nonlinear optical devices can be difficult. This problem can be solved in some cases by the use of interacting waves with orthogonal polarizations (type II phase matching). However, this approach generally precludes the use of the largest nonlinear coefficient and is incompatible with well-developed material systems, such as proton-exchanged waveguides in lithium niobate, that guide a single polarization. In quasi-phase-matched (QPM) waveguide devices, interferometer structures can separate mixed output from pump and signal input, making the use of wavelength-selective filters unnecessary; this device is an optical-frequency balanced mixer.[1] An alternative approach is quasi-phase matching between higher-order waveguide modes of the interacting waves; odd and even modes can be filtered or separated with integrated optical components. In the early development of guided-wave nonlinear optics the phase-matching requirement often led to the use of higher-order mode interactions.[2] More recently, engineering the depth dependence of the nonlinear coefficient has improved mode overlap efficiency in thin-film waveguides that use higher-order modes[3] and in QPM channel waveguides with nonuniform domain inversion.[4] Here we demonstrate high-precision QPM structures with transverse patterning optimized for efficient higher-order mode mixing, with the end goal of generating distinguishable outputs.

Although waveguide quasi-phase matching most often involves the fundamental modes of the interacting wavelengths, the technique also applies to mixing of higher-order modes. In waveguide QPM interactions, nonlinear mixing efficiency η is proportional to the spatial overlap of $\overline{d}$, the phase-matched Fourier component of the grating (which is a periodic modulation of the nonlinear coefficient d along the z direction) and the normalized mode fields, E_{jk}:

$$\eta \propto \left| \iint_{\infty}^{-\infty} \overline{d}(x,y) E_{1,jk}(x,y) E_{2,lm}(x,y) \times E_{3,np}{}^{*}(x,y)\,\mathrm{d}x\,\mathrm{d}y \right|^2, \qquad (1)$$

where (x, y) are transverse to the propagation direction, z.[4] Figure 1 depicts this coordinate system in which standard QPM gratings, formed along the x direction, overlap waveguides lying along the z direction. The first subscript of each interacting field E identifies the frequency ($\omega_3 = \omega_1 + \omega_2$), and the two lettered subscripts are width and depth mode numbers. In this study we focus on the specific but common case of second-harmonic generation (SHG) using a first-harmonic (FH) wave in the fundamental mode (00 mode), such that $E_{1,00} = E_{2,00}$ in relation (1). With this FH mode we demonstrate efficient quasi-phase matching for both the fundamental and the first higher-order width (x coordinate) modes of the second-harmonic (SH) wave: $E_{3,00}$ and $E_{3,10}$.

QPM grating fabrication techniques, such as electric-field poling of ferroelectrics, often yield structures in which $d(x, y)$ is constant over the extent of the waveguide. With these standard gratings, odd second-harmonic (SH) modes cannot be produced from even FH modes because of the symmetry of the coupling coefficient in relation (1); two even modes mixing with an odd mode under an even d have a null efficiency overlap integral. For standard channel waveguides—and all waveguides with symmetric and antisymmetric width modes—QPM SHG cannot produce $E_{3,10}$ from $E_{1,00}$ unless the symmetry in x is broken.

Modified QPM gratings can alter the symmetry of $d(x)$, permitting quasi-phase matching of odd width modes. Angled gratings that are tilted with respect to the waveguides (Fig. 1) give d an x-dependent phase $\phi = 2\pi x \tan\theta/\Lambda$, where θ is the grating angle with

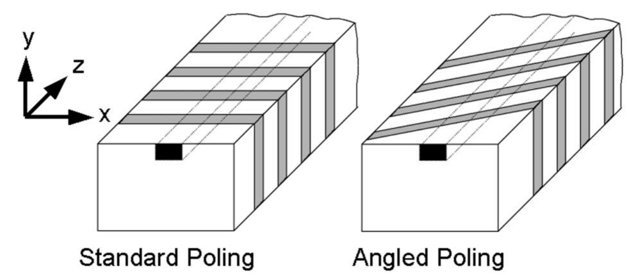

Fig. 1. Coordinate system and geometry for standard and angled QPM gratings and waveguides.

respect to x and Λ is the QPM period. As a result, d is neither even nor odd, and both types of mode can be generated. Staggered gratings—nearly interleaved gratings with a π-phase shift at the center of the waveguide—make d fully antisymmetric in x (Ref. 5) and are optimal for generating the two-lobed 10 mode. Note that, although altering the symmetry of d can ensure nonzero efficiency for odd mode quasi-phase matching, this efficiency is still proportional to the mode overlap. In general, using higher-order modes rather than the fundamental modes in symmetric waveguides degrades mode overlap because of the additional minima in the modal fields.

Annealed proton-exchanged waveguides in periodically poled lithium niobate (PPLN) are among the most efficient nonlinear mixing devices available[6] and are well suited for odd mode quasi-phase matching. We found that PPLN gratings angled at 60° to x are easily fabricated because of the hexagonal domain structure of congruent lithium niobate. Using narrow (as measured perpendicularly to the k vector) stripes, we also fabricated nearly ideal staggered gratings by accounting for domain spreading along x during poling. Figure 2 shows standard, angled, and staggered gratings (15-μm period, 35 and 50 μm in width) precisely aligned to waveguides and etched for visibility; the etching enlarges and rounds the edges of the inverted domains slightly. These devices had QPM periods of 14.75–16.75 μm, waveguide widths ranging from 8 to 20 μm, and an initial proton-exchange depth of 0.8 μm.

SHG measurements with the TM_{00} mode of the FH (tuned from 1540 to 1565 nm) demonstrated efficient generation of both TM_{00} and TM_{10} SH modes. CCD images of both modes in 8-μm waveguides (with different QPM periods) are shown in Fig. 3; in the shading scheme used, the highest and lowest intensity points appear black. Normalized conversion efficiencies as high as 400%/W and 220%/W for the TM_{00} and TM_{10} modes, respectively, were measured in devices with 4-cm-long angled gratings. With standard gratings, only the TM_{00} mode could be phase matched (900%/W efficiency), as expected. Figure 4 compiles measurements (represented by open circles) of the SHG efficiency of both modes (using 60°-angled and standard gratings) for a wide range of waveguide widths. The solid curves are efficiency calculations based on modal fields obtained with our waveguide fabrication model.[7] As shown, this model successfully predicts the relative SHG efficiencies for both modes for all the waveguide widths tested.

The staggered grating devices, which have far more stringent alignment tolerances between the periodic poling and the waveguides, showed approximately half of the expected TM_{10} mode SHG efficiency. Mode overlap calculations indicate that this reduction is consistent with a misalignment in x (assuming perfect angular alignment) of ~1.0 μm. A vernierlike system of deliberate misalignments could compensate for fabrication errors in future devices. Nonzero generation of the TM_{00} SH mode also indicated poling-waveguide misalignment, because staggered grating devices should generate only odd modes. Figure 5 compares calculated SHG efficiencies for all three poling types, for the range of waveguides fabricated in this study. An ideal staggered poling device should have roughly twice the 10-mode SHG efficiency of a 60°-angled poling device and ~70% of the 00 mode SHG efficiency of a standard poling device.

Angled and staggered gratings permit QPM interactions between odd and even modes of waveguides that are symmetric in x. PPLN waveguide modes are not symmetric in y, however, because asymmetric depth profiles for the refractive index and the nonlinear

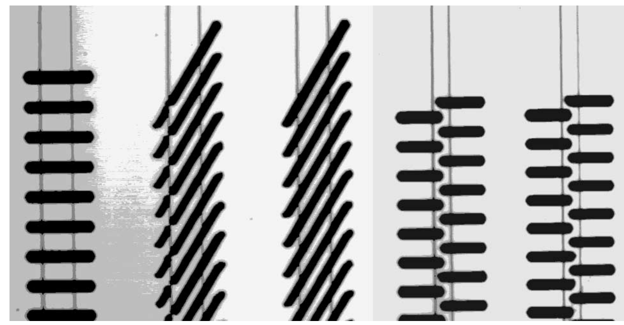

Fig. 2. Standard, 60°-angled, and staggered PPLN gratings (15-μm period, 35 and 50 μm in width) aligned to waveguides and etched for visibility.

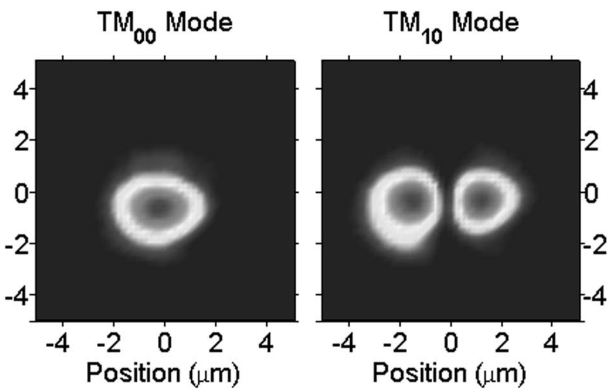

Fig. 3. CCD camera images of TM_{00} and TM_{10} modes at the SH wavelength.

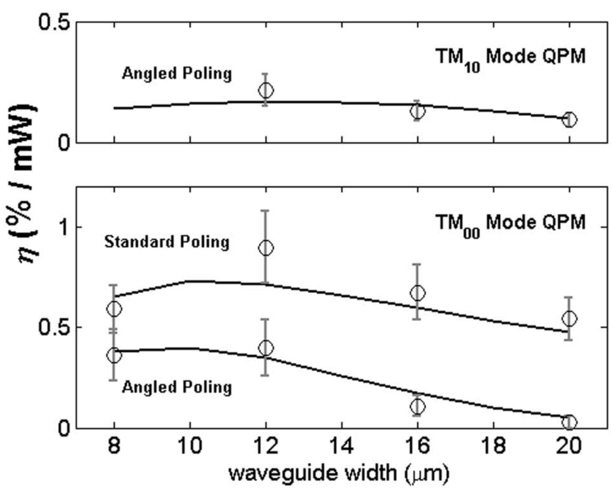

Fig. 4. Measured (open circles) and calculated (solid curves) SHG efficiencies for TM_{00} and TM_{10} modes for 60°-angled and standard poling and a range of waveguide widths.

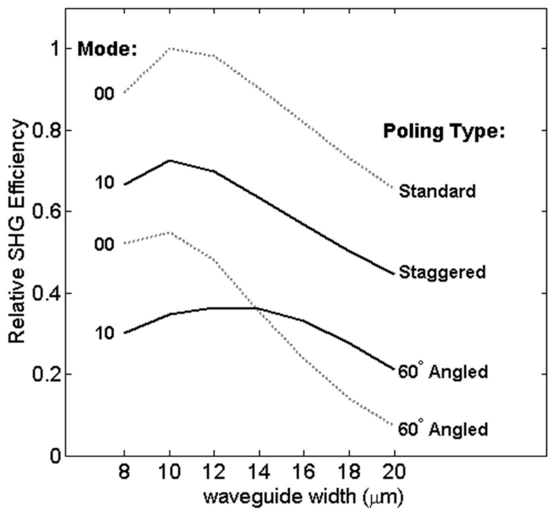

Fig. 5. Calculations of the expected relative SHG efficiencies of standard, 60°-angled, and staggered poling for a range of waveguide widths. With successful fabrication, TM_{10} mode SHG devices with staggered gratings should have ~70% of the efficiency of standard TM_{00} mode SHG devices.

coefficient $d(y)$ result from the annealed proton-exchange process. Consequently, SHG of TM_{01} modes (higher order in depth) is possible with a TM_{00} mode FH input.[8,9] In similar fashion, modified gratings could complement PPLN waveguides with x asymmetry for efficient generation of asymmetric width modes.

In summary, control of the symmetry of d with modified gratings adds flexibility in choosing which waveguide modes will interact in a QPM device. This research has demonstrated the generation of odd and even modes by use of SHG. In optical signal processing applications, QPM waveguide devices are often used in a difference-frequency generation or a cascaded $\chi^{(2)}$ configuration.[10,11] Here odd and even modes for the signal and idler waves, combined with integrated structures for mode filtering, would solve the problems of distinguishability and spatial separation of the output and residual input.

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