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Intensity-Dependent Mode Competition In 2Nd-Harmonic Generation In Multimode Wave-Guides

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Second harmonic generation (SHG) in waveguides which are multimode at the second harmonic exhibit an intensity dependence in both the phase-match wavelength and relative conversion efficiency of the different SHG modes because they are coupled to the same fundamental. © *1995 American Institute of Physics.*

The reasons for using waveguides for second harmonic generation (SHG) are well documented.[1,2] The spatial confinement to beam cross-sectional areas of the order of the wavelength squared for centimeter distances results in high conversion efficiencies at relatively low input power levels. Furthermore, because waveguides can support multiple modes at the same frequency but with different wave vectors, there is much more flexibility in wave vector matching than is available with plane wave interactions in bulk media. There is a price for this additional flexibility, namely the field overlap with higher order modes can reduce the overall conversion efficiency. In this letter we discuss another limitation imposed by some waveguides when large conversion efficiencies are desired.

The invention of quasi-phase-matching (QPM) and segmented phase-matching techniques have allowed the large diagonal second-order coefficients of $LiNbO_3$ and KTP to be effectively used for waveguide SHG.[3,4] Typically, a waveguide which is single mode at the fundamental wavelength [e.g., $TM_{00}(\omega)$] is multimode for the second harmonic [e.g., $TM_{p,q}(2\omega)$, where p and q are the mode numbers]. Due to the small refractive index differences produced by waveguide fabrication techniques in these materials, the harmonic guided modes can be very closely spaced in wave vector and can be simultaneously generated. It has recently been appreciated that any second-order process leads to a nonlinear dispersion with the wavelength in the phase for all of the interacting beams.[5] When a fundamental guided mode results in two or more harmonic modes which differ in mode numbers p and q, the nonlinear phase shift induced by one harmonic can affect the phase-matching condition for another harmonic mode detuned from it by many SHG bandwidths. That is, power exchange between one of these SH modes and the fundamental can lead to a nonlinear phase shift for the other SH modes. For large conversion efficiencies and closely spaced modes we have found experimentally and theoretically that the second harmonic generation process can be severely distorted by this nonlinear phase change. In fact, this effect had been suspected to be responsible for the detuning asymmetries found in the first experiments on cascading in KTP waveguides.[6]

This effect was modeled using the standard coupled-mode equations that describe SHG with two SH modes interacting simultaneously with the fundamental. These equations are

$$\frac{dA}{dz}=i\kappa_1 B_1 A^* e^{i\Delta k_1 z}+i\kappa_2 B_2 A^* e^{i\Delta k_2 z},$$

$$\frac{dB_1}{dz}=i\kappa_1 A^2 e^{-i\Delta k_1 z},$$

$$\frac{dB_2}{dz}=i\kappa_2 A^2 e^{-i\Delta k_2 z},$$

where the complex amplitudes of the interacting waves are written as A for the fundamental and B_i (i=1,2) for the harmonics. This required introducing two more variables than are found in the usual SHG problem which involves a single second harmonic; namely, an effective nonlinear coefficient κ_2 describing the "strength" of the interaction of the second mode with the fundamental (κ_1 is for the first mode), and Δk_2, the wave vector detuning for the second low power harmonic. In fact, analysis of the equations shows that the difference between the detunings, $\Delta k_0 L=\Delta k_2 L-\Delta k_1 L$, along with $\Delta k_1 L$ are the relevant detuning parameters.

We evaluated this set of equations numerically, varying the input fundamental intensity ($I_0=|A(z=0)|^2$), the ratio of the interaction strengths (κ_2/κ_1), and the detuning between the harmonic modes, $\Delta k_0 L$. We ignore coherent interaction between SH modes. We found for the different ratios of the interaction strengths that the effective SHG detuning curves for low fundamental depletion (less than 10% conversion efficiency) or large separation ($\Delta k_0 L$ larger than 25π) always behaved independently for the two SH modes. In the case of larger depletion and close separation the two SH modes "talk" to each other via the fundamental mode. Some of the general features that we found are that the wavelength and peak conversion efficiency for the two different

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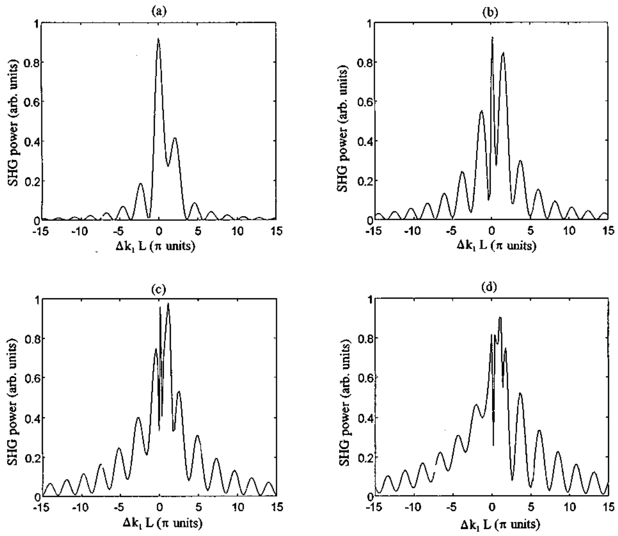

FIG. 1. SHG detuning curve for different normalized input powers. (a) $I_0=0.25$, (b) $I_0=1.0$, (c) $I_0=2.25$, and (d) $I_0=4.0$. In all cases $\kappa_1 L=4$, $\kappa_2 L=1.5$, and $\Delta k_0 L=2\pi$.

harmonic modes changes with input fundamental intensity and that power-dependent competition occurs between them at high powers.

Calculations based on experimental parameters are shown in Figs. 1 and 2. Specifically, a QPM $LiNbO_3$ channel waveguide was assumed, 4 μm wide and 3 μm deep. It supports only the TM_{00} fundamental mode around 1.6 μm. It was designed to optimize the overlap between the fundamental and the TM_{01} SH fields. This also resulted in a small effective index difference between the TM_{01} and TM_{20} modes, with a larger overlap integral for the SHG of $TM_{01}(2\omega)$ than for $TM_{20}(2\omega)$. A reasonable approximation for our waveguide is $\Delta k_0 L \sim 2\pi$ and $\kappa_1 L=4$ and $\kappa_2 L=1.5$, based on a calculated effective index difference of 0.0001 and on overlap integrals with triangular domain inversion regions.[7] A series of SHG detuning curves are shown in Fig. 1 for different input fundamental powers. In Fig. 1(a), the SHG output is essentially a linear superposition of the response curves for the two second harmonic modes acting independently. As the normalized input power is increased, the response becomes much more complicated. There is no single well-defined peak for zero detuning of the TM_{01} mode and the largest conversion efficiency shifts to nonzero detuning. In fact, if the fundamental wavelength is fixed, increasing the input power would lead to oscillations in the second harmonic. This implies that optimizing the peak conversion efficiency requires power-dependent retuning of the input laser wavelength. The total nonlinear phase shift imparted onto the fundamental is shown in Fig. 2. The shift in the zero nonlinear phase shift point clearly moves toward positive detuning. Furthermore, note that for large input powers, Fig. 2(d), zero net nonlinear phase shift occurs for multiple detunings implying a series of peaks in the conversion efficiency corresponding to different wavelengths.

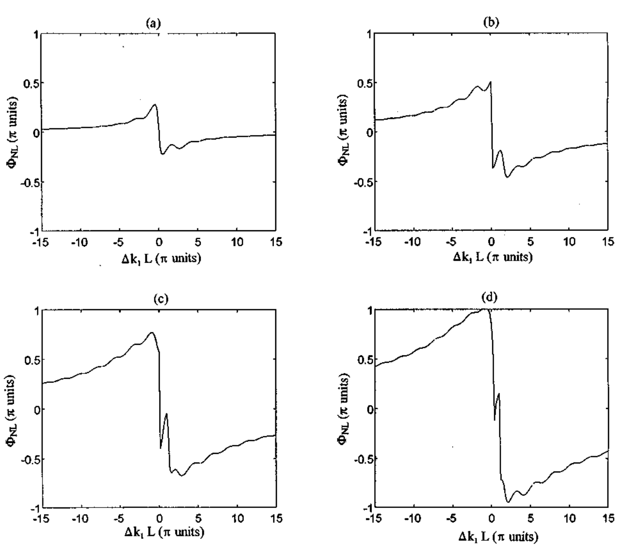

FIG. 2. Total nonlinear phase shift for (a) $I_0=0.25$, (b) $I_0=1.0$, (c) $I_0=2.25$, and (d) $I_0=4.0$. In all cases $\kappa_1 L=4$, $\kappa_2 L=1.5$, and $\Delta k_0 L=2\pi$.

Experiments to confirm this behavior were performed on a QPM $LiNbO_3$ waveguide (20 μm domain reversal period) made using standard proton exchange techniques.[8] The waveguides used had an effective depth of 3 μm and channel widths varying from 1 to 7 μm. A synchronously mode-locked color center laser operated in either its mode-locked (ML, 76 MHz, 6 ps pulses) or quasi-continuous-wave (QCW) modes was used for the fundamental. The laser was tunable from 1520 to 1645 nm. Using both configurations allowed us to verify that the changes we observed were not thermal.

Wavelength scans around the ($TM_{00} \rightarrow TM_{01} + TM_{20}$) interaction are shown in Fig. 3 for a 4 μm wide channel waveguide. The generation of both SH modes was confirmed by observing the spatial power distribution at the output under different input conditions. At low conversion efficiencies (less than 1%: QCW) the wavelength detuning curves are similar to the calculated ones [Fig. 1(a)]. Note that for comparable average powers in both cw and mode-locked operation, the detuning curves are very different, indicating that thermal effects are not responsible for the observed changes. As expected, increasing the peak input power increases the SHG efficiency, from 0.005% to 27% for the cases shown in Fig. 3. At large conversion efficiencies (more than 10%: ML) the maxima shift position, come closer to each other and compete for the maximum SHG efficiency. This type of behavior is quite general and was observed for different waveguides at different wavelengths, independent of the coupling strength ratio κ_2/κ_1. These results are all in qualitative agreement with the theory discussed above.

This behavior can be understood in terms of the cascaded nonlinearity which produces nonlinear phase shifts in both the fundamental and harmonic modes. Maximum SHG occurs for a harmonic beam when the photons returning from the harmonic via down-conversion back to the fundamental are π out of phase with the fundamental. This ensures maximum depletion of the fundamental. However, when another second harmonic mode interacts with the same fundamental, it produces a nonlinear phase shift on the fundamental, for example, $+\phi^{NL}(z)$. As a result the down-shifted fundamental photons are now out of phase with the fundamental. By

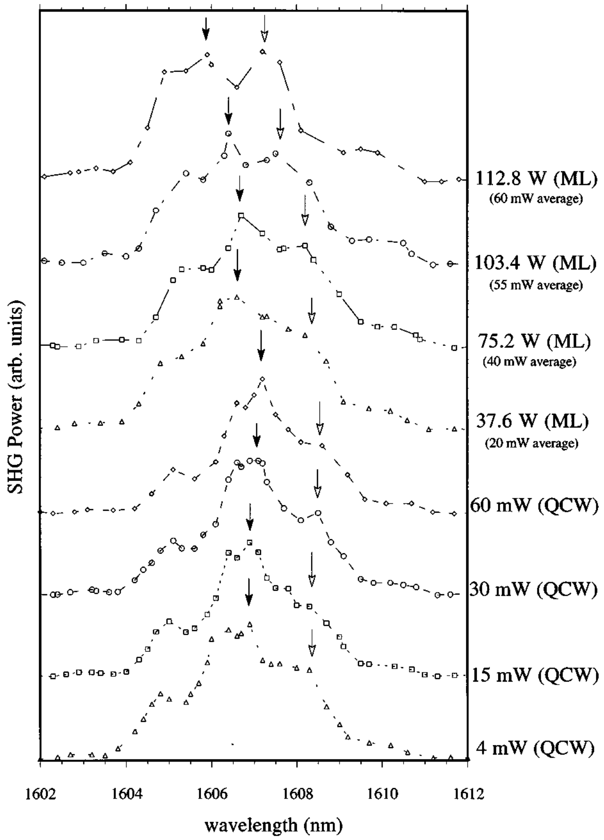

FIG. 3. Wavelength scan in the $LiNbO_3$ QPM waveguide at different peak powers in the vicinity of $TM_{00}(\omega)\rightarrow TM_{01}(2\omega)+TM_{20}(2\omega)$. Solid (open) arrows track the position of the peak conversion to the $TM_{01}(TM_{20})$ mode. Conversion efficiencies on the solid arrows for these curves are (bottom to top): 0.005%, 0.069%, 0.33%, 0.63%, 17%, 21%, 23%, and 27%, respectively.

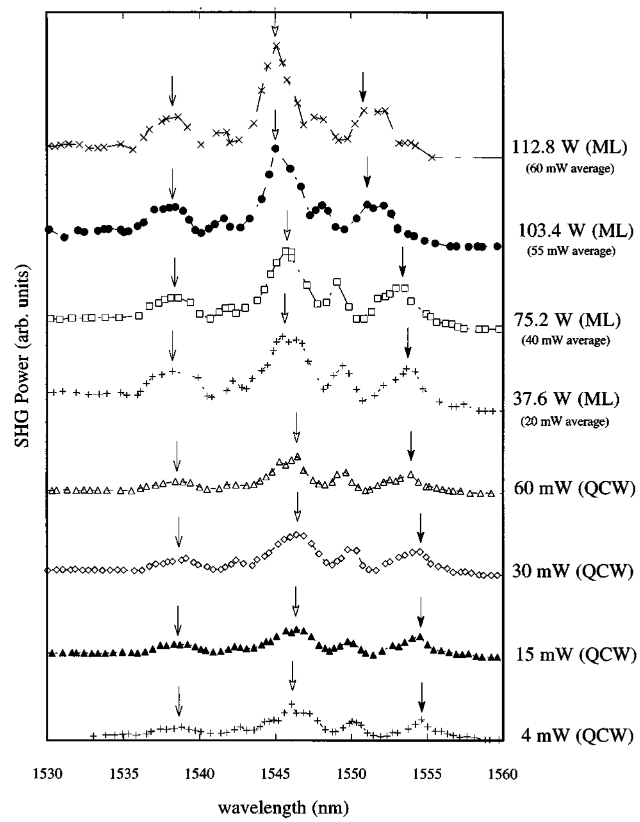

FIG. 4. Wavelength scan in the $LiNbO_3$ QPM waveguide at different peak powers in the vicinity of the interaction $TM_{00}(\omega)\rightarrow TM_{02}(2\omega)+TM_{40}(2\omega)+TM_{21}(2\omega)$. These curves were normalized to the solid arrow points in Fig. 3. Point (open and solid) arrows track the position of the peak conversion to the $TM_{21}(TM_{40}$ and $TM_{02})$ mode.

detuning from the low-power wave vector matching condition by $-\Delta k_1$, maximum conversion of the harmonic can again be obtained. As a result, the wavelength for maximum conversion changes.

In the same 4 μm wide channel waveguide, for the interaction $TM_{00}\rightarrow TM_{02}+TM_{40}+TM_{21}$, second harmonic modes are all closely spaced. The spatial distribution of the SHG verified the presence of all of these modes. The evolution of SHG with increasing input power is very complicated, as shown in Fig. 4. The behavior shown in this figure indicates a complex SHG evolution which will require in this case a four-coupled mode equations theoretical analysis instead of three independent pair of coupled mode equations describing three independent SH modes.

In summary, second harmonic generation can be a very complex process when two closely spaced harmonic modes are possible. Competition for power occurs due to the common coupling to the fundamental beam and the peak efficiency wavelength shifts due to the nonlinear phase shifts introduced by the neighboring mode. This effect has been predicted numerically and verified experimentally in QPM $LiNbO_3$ waveguides. Although the experiments were performed under conditions of very strong coupling, calculations show that such effects occur out to detunings of 25π between the two harmonic modes.

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