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Michael Sundheimer, Pierre Aschieri and Pascal Baldi, John Bierlein

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Modeling and experimental observation of parametric processes in segmented KTiOPO_4 channel waveguides

Michael Sundheimer^{a)}

Department of Physics, Koç University, Istinye, 80860 Istanbul, Turkey

Pierre Aschieri and Pascal Baldi

Laboratoire de Physique de la Matière Condensée, Université de Nice–Sophia Antipolis, 06108 Nice cedex 2, France

John Bierlein

Du Pont Experimental Station, Wilmington, Delaware 19880

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This letter presents a modeling technique for quasiphase-matched parametric processes in segmented channel waveguides and the results of measurements of infrared parametric fluorescence in segmented KTiOPO_4 channel waveguides. We demonstrate both theoretically and experimentally a strong dependence of optical parametric oscillator tuning curves and parametric conversion efficiency (parametric gain) on the segmentation duty cycle. We show that the optimum conversion efficiency for parametric interactions in segmented waveguides is obtained for duty cycles greater than 50%. Our results validate the use of an effective continuous waveguide model for segmented channel waveguide calculations over a wide range of wavelengths and duty cycles.

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There is substantial progress being made in the use of quasiphase matching (QPM) in periodically poled $\chi^{(2)}$ materials for parametric processes such as sum- and difference-frequency generation and for optical parametric oscillators (OPOs). Both bulk and waveguide QPM OPOs have been realized recently in LiNbO_3 ,^{1,2} with the waveguide geometry offering significant potential advantages such as low-voltage electro-optic tuning, direct laser diode or fiber-optic butt coupling, and on-chip integration with other photonic devices. Segmented KTiOPO_4 (KTP) waveguides have been successfully employed for second-harmonic generation (SHG) and are also promising for integrated OPOs since they do not appear to suffer from the two main disadvantages of LiNbO_3 waveguides: a low photorefractive damage threshold and the possible destruction of the domain-inversion structure during annealed proton exchange (APE) waveguide fabrication.³ The availability of the segmentation duty cycle as an additional design parameter is also an advantage over nonsegmented geometries.

In this work we have investigated both theoretically and experimentally the use of segmented KTiOPO_4 waveguides for parametric frequency conversion and integrated OPO applications by measuring parametric fluorescence, allowing us to determine the OPO tuning curves (equivalent to sum- and difference-frequency QPM wavelengths), the parametric gain, and the predicted threshold pump power of an OPO that could be built from these guides without the need to actually realize an OPO. We provide experimental evidence over a very wide range of wavelengths that validates the use of an effective continuous waveguide model for segmented waveguide calculations. We also show that the duty cycle is a potentially useful adjustable design parameter for frequency conversion in segmented waveguides by measuring its influence on OPO tuning curves, OPO degeneracy wave-

lengths (equivalent to SHG wavelengths), and parametric conversion efficiency.

Parametric fluorescence can be thought of as the spontaneous splitting of a pump photon of wavelength λ_p into signal and idler photons of wavelengths λ_s and λ_i , respectively, in a second-order nonlinear medium. Equivalently, one can consider that parametric fluorescence is generated by the mixing of pump photons with quantum vacuum fluctuations (noise photons) at the signal and idler frequencies.⁴ In either picture, energy must be conserved, and in order for the process to be efficient, momentum conservation, or phase matching, must be satisfied. Thus, the two basic equations governing the process in a quasiphase-matched waveguide are

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}, \quad (1)$$

$$\frac{n_{\text{eff}}^p}{\lambda_p} - \frac{n_{\text{eff}}^s}{\lambda_s} - \frac{n_{\text{eff}}^i}{\lambda_i} - \frac{m}{\Lambda} = 0, \quad (2)$$

where the n_{eff} 's are the effective indices of the pump, signal, and idler modes in the waveguide, Λ is the QPM domain-inversion grating period, and m is the QPM order ($m=1$ in this case).

Parametric fluorescence acts as a gain mechanism for fields at the signal and idler frequencies, thus one can have parametric amplification and oscillation. The waveguide small-signal parametric gain parameter g (such that the power gain $G = g^2 L^2$, where L is the length of the nonlinear medium) is given at phasematching by^{5,6}

$$g^2 = \frac{8\pi^2 P_p(0) I}{c \epsilon_0 \lambda_s \lambda_i n_{\text{eff}}^p n_{\text{eff}}^s n_{\text{eff}}^i}, \quad (3)$$

where $P_p(0)$ is the pump power in the waveguide at the input end, c and ϵ_0 are the speed of light and permittivity of

^{a)}Electronic mail: msundheimer@ku.edu.tr

free space, and I is the nonlinear modal overlap integral given by the following equation:

$$I = d_{\text{eff}}^2 \frac{[\iint E_p(x,y)E_s(x,y)E_i(x,y)dxdy]^2}{\iint E_p^2(x,y)dxdy \iint E_s^2(x,y)dxdy \iint E_i^2(x,y)dxdy}. \quad (4)$$

In Eq. (4), x and y are the transverse spatial coordinates; the E 's are the electric-field amplitudes of the pump, signal, and idler modes; and d_{eff} is the effective nonlinear coefficient, which for a rectangular QPM grating in first order is given by

$$d_{\text{eff}} = \frac{2d_{33}}{\pi} \sin(\pi D). \quad (5)$$

Here, D is the duty cycle of the QPM grating, defined as the ratio of exchanged to unexchanged segment lengths. Thus, $D=50\%$ results in the largest d_{eff} . In our calculations we use $d_{33}=15$ pm/V for KTiOPO₄. In general, the d coefficient can be a function of the spatial coordinates (in which case, it should be included in the numerator integral), either through variations in d_{33} resulting from the ion-exchange process, or through a depth-dependent duty cycle as would be encountered with nonrectangular domains. For this study, we have used a spatially uniform d_{33} extending to a given depth below the surface, beyond which we have taken $d_{\text{eff}}=0$ to model the lack of domain inversion at greater depths which can occur in domain inversion created by ion exchange.

It can be shown that the parametric fluorescence power at the signal wavelength after a propagation length L is related to the parametric gain parameter by⁵

$$P_s(L) = \frac{hc^2 \Delta\lambda_s}{\lambda_s^3} \left(\frac{1 - e^{-\alpha_p L}}{\alpha_p L} \right) e^{-2\alpha L} g^2 L^2, \quad (6)$$

where h is Planck's constant, $\Delta\lambda_s$ is the full width at half maximum bandwidth of the signal fluorescence, α is the loss at the signal and idler wavelengths (assumed equal, which is valid if not too far from degeneracy), and α_p is the loss at the pump wavelength. Thus, measurement of parametric fluorescence power as a function of pump wavelength and power not only yields the signal and idler wavelengths (the tuning curve of an OPO built from the guide), but also the OPO gain, and from this the expected threshold pump power for given OPO cavity mirror reflectivities.

Since $P_s(L)$ depends on the pump power and guide length, it is useful to express the fluorescence efficiency in a normalized form, which also provides a direct comparison to the waveguide second-harmonic generation results reported in the literature. In analogy to second-harmonic generation, we define the normalized conversion efficiency as

$$\begin{aligned} \eta' &= \frac{P_s(L)}{P_p(0)P_i(0)L^2} \\ &= \frac{P_s(L)\lambda_s^3}{P_p(0)hc^2\Delta\lambda_s L^2} = \frac{g^2}{P_p(0)L^2} \left(\frac{1 - e^{-\alpha_p L}}{\alpha_p} \right)^2 e^{-2\alpha L}. \end{aligned} \quad (7)$$

The waveguides, fabricated at Du Pont, using standard ion-exchange techniques,⁷ have five different QPM segmentation duty-cycles D . Each guide is $5 \mu\text{m}$ wide, 3.5 mm long, and has a QPM period Λ of $25 \mu\text{m}$. A cw single-longitudinal-mode Ti:sapphire laser was used as the pump

FIG. 1. Measured and calculated tuning curves for various segmentation duty cycles. The measured signal wavelengths are the solid circles, the idler wavelengths (calculated by conservation of energy) are the solid squares, and the results of the numerical modeling are the open diamonds.

source. The incident pump power on each guide was 100 mW. Waveguide throughputs varied from 15% to 30%. The resulting parametric fluorescence spectrum was measured using a monochromator, a low-noise liquid-nitrogen-cooled germanium detector, and lock-in amplifier, as described elsewhere.⁵ All fields are in the TM₀₀ mode. The signal wavelength was measured directly from the fluorescence spectrum, and the corresponding idler wavelength, which was typically beyond the cutoff of the detector, was calculated using Eq. (1). By varying the pump wavelength, the QPM tuning curves were measured for each waveguide, as shown in Fig. 1.

Also shown in Fig. 1 are the results of numerical calculations using a modified effective-index waveguide modeling program. To achieve these fits, we used the following reasonable parameters for ion-exchanged KTiOPO₄ waveguides: an exponential refractive index profile in the

FIG. 2. Degeneracy wavelengths as a function of the segmentation duty cycle. The solid line through the data points is the least-squares best fit.

FIG. 3. Measured (points) and theoretically calculated (solid line) parametric fluorescence efficiency for various duty cycles.

depth direction ($1/e = 12 \mu\text{m}$), a $5 \mu\text{m}$ wide step index profile in the width direction, and a surface $\Delta n = 0.03$ in the ion-exchanged regions. The predicted QPM wavelengths are quite sensitive to the waveguide parameters, and no other set of reasonable parameters yielded good agreement between theory and experiment for all five waveguides over the entire signal-idler wavelength range. We modeled the waveguide segmentation by modeling the guides as effective continuous guides with a weighted-average surface $\delta n = D\Delta n$.^{8,9} The excellent fits over the large wavelength range and for several duty cycles indicate that the effective continuous waveguide model, developed rigorously only for segmented planar waveguides, is also useful for segmented channel waveguides. Notice that in the segmented waveguides, unlike in electric-field poled materials such as PPLN, the ion exchange not only inverts the ferroelectric domains but also increases the refractive index, causing the tuning curves to shift as the duty cycle changes.

Infrared wavelengths from 1.1 to $2.9 \mu\text{m}$ were generated using pump wavelengths from 790 to 850 nm , which are easily available from inexpensive laser diodes. It is also interesting to look at the dependence of the pump degeneracy wavelengths (equal to one-half the phase-matching wavelengths for infrared to near-infrared SHG) on the duty cycle, as shown in Fig. 2. We find a linear dependence of the degeneracy point on the duty cycle for these guides. This is a potentially useful relationship for QPM-segmented waveguide design for parametric interactions.

In segmented waveguides there is a trade off between stronger modal confinement and reduced d_{eff} as the duty cycle is increased above 50% , yielding a maximum nonlinear overlap integral and an optimum conversion efficiency for $D > 50\%$. This is shown in Fig. 3, where we plot as a function of the duty cycle the measured and the theoretically calculated (using the waveguide modeling program with the same parameters as used for the tuning curves) fluorescence efficiency for a domain-inversion depth of $2.4 \mu\text{m}$. This depth gives theoretical fluorescence efficiencies in agreement with the measured values for all guides. Although the waveguides are much deeper than this, domain inversion may not occur over the entire guide depth.¹⁰ A maximum

normalized efficiency of $0.57\%/W \text{ cm}^2$ was measured for the $D = 60\%$ guide. Using in Eq. (6) the measured values for the signal power, the signal bandwidth, the pump power in the guide of $P_p(0) = 22 \text{ mW}$, and assuming loss coefficients for the signal and idler of $\alpha = 0.2 \text{ cm}^{-1}$ and for the pump of $\alpha_p = 0.4 \text{ cm}^{-1}$, the gain parameter was calculated to be $g = 0.013 \text{ cm}^{-1}$. Assuming OPO cavity mirror reflectivities of 100% and 99% , the resulting doubly resonant OPO threshold power is approximately 25 W in the guide. This is much too high for a cw-integrated OPO, but proper waveguide design and deeper domain-inversion depth could substantially increase the parametric gain coefficient and reduce this threshold to achievable cw powers. For example, for a domain-inversion depth equal to the guide $1/e$ depth of $12 \mu\text{m}$, the predicted OPO threshold reduces to 350 mW . Lower waveguide losses would further reduce this threshold to easily achievable diode pump laser powers. We should also mention that in this model we have neglected the variation in losses as a function of the duty cycle, which is predicted in segmented waveguides.^{8,9} Our chosen losses are the maximum predicted for wavelengths not near Bragg resonances. The gain coefficient and parametric efficiency are not very sensitive to the losses for small losses, while the OPO threshold is quite sensitive to losses, decreasing significantly with reduced losses.

In conclusion, we have shown that segmented KTiOPO_4 waveguides can be useful for parametric interactions well into the infrared, and that optimized guides are potential candidates for use in low-threshold integrated OPOs. Our results indicate that it is possible to apply the effective continuous waveguide model to segmented channel waveguides for a wide range of wavelengths and segmentation duty cycles. We have shown that the QPM tuning curves of segmented waveguides vary strongly with the duty cycle, yielding a linear dependence of OPO degeneracy or SHG wavelength on the duty cycle over a wide range of duty cycles. Additionally, unlike in nonsegmented QPM geometries such as PPLN, the optimum duty cycle for nonlinear frequency conversion in segmented waveguides is shown to be greater than 50% .

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