Thin film wavelength converters for photonic integrated circuits: supplementary material

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This document provides supplementary information to “Thin film wavelength converters for photonic integrated circuits,” <http://dx.doi.org/10.1364/optica.3.000531>, concerning the theory of second harmonic generation (SHG) for quasi-phase-matched (QPM) waveguides. It also provides the analysis of the drop of efficiency and the broadening of bandwidth for the PPLN devices we demonstrated. © 2016 Optical Society of America

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1. Theory for second-harmonic generation in PPLN devices

The second-harmonic power $P_{2\omega}$ generated by a device with waveguide length L can be expressed as [1,2]:

$$P_{2\omega} = \eta_{\text{nor}} L^2 P_{\omega}^2 g(L), \quad (\text{S1})$$

where P_{ω} is the pump power and:

$$\eta_{\text{nor}} = \frac{8d_{33}^2}{\epsilon_0 c n_{\omega}^2 n_{2\omega}^2 \lambda_{2\omega}^2 S_{\text{eff}}} \text{sinc}^2(L\Delta k / 2), \quad (\text{S2})$$

is the normalized efficiency expressed in $\text{W}^{-1}\cdot\text{cm}^{-2}$. In this last expression, d_{33} is the nonlinear coefficient of the material, ϵ_0 is the vacuum permittivity, c is the speed of light in vacuum, n_{ω} and $n_{2\omega}$ are the effective refractive indices for the fundamental mode and the second-harmonic mode, respectively. Also:

$$\Delta k = k_{2\omega} - 2k_{\omega} + 2\pi\Lambda^{-1}, \quad (\text{S3})$$

is the wave number mismatch with the QPM structure of period Λ . The overlap integral between the interacting waveguide modes at ω and at 2ω is defined by:

$$S_{\text{eff}} = \frac{\left[\iint E_{\omega}^2(x, y) dx dy \right]^2 \iint E_{2\omega}^2(x, y) dx dy}{\left[\iint d(x, y) E_{\omega}^2(x, y) E_{2\omega}(x, y) dx dy \right]^2}, \quad (\text{S4})$$

where $E(x, y)$ is the spatial mode profile of transverse waveguide modes and $d(x, y)$ is the normalized nonlinear coefficient. S_{eff} mainly depends on two factors: the mode size at the different wavelengths and the overlap between them. Finally, the loss factor $g(L)$ is expressed as:

$$g(L) = e^{-(\alpha_{\omega} + \alpha_{2\omega})L} \frac{(e^{\Delta\alpha L} + 1)^2 - 4\cos^2(L\Delta k / 2)e^{\Delta\alpha L}}{(\Delta\alpha)^2 + (\Delta k)^2}, \quad (\text{S5})$$

where:

$$\Delta\alpha = \alpha_{\omega} - \frac{\alpha_{2\omega}}{2}. \quad (\text{S6})$$

If $\Delta\alpha = 0$, equation (S1) reduces to:

$$P_{2\omega} = \eta_{\text{nor}} L^2 P_{\omega}^2 e^{-2\alpha_{\omega}L} \Leftrightarrow \eta_{\text{nor}} = \frac{P_{2\omega}}{L^2 P_{\omega}^2} e^{2\alpha_{\omega}L}. \quad (\text{S7})$$

This last expression is used to determine experimentally the normalized efficiency of the PPLN device for SHG.

Fig. S1. Normalized efficiency calculated from (S2) as a function of the pump wavelength

The spectral dependence of the normalized efficiency for the PPLN waveguide we designed is simulated in Fig. S1 using (S7) and $d_{33} = 27 \text{ pm/V}$ [3]. The peak efficiency is $1600 \% \text{ W}^{-1} \cdot \text{cm}^{-2}$ at the central working wavelength of 1530 nm . The 3-dB bandwidth is $\sim 1 \text{ nm}$. The function is proportional to the square of a cardinal sine (sinc), as the waveguide is assumed to be perfectly uniform. This requires constant waveguide geometry, 100-% poling yield, 50-% duty cycle and fully overlap between the mode and the poled region.

In comparison, the bandwidth of the measured efficiency (see Fig. 4(a)) is 3 times larger and the peak value 10 times smaller. In addition, the spectral dependence slightly differs from the square of a sinc. This suggests that the waveguide is not perfectly uniform. Several causes can explain the non-uniformity: the non-uniformity of the waveguide and poling electrode geometry due to fabrication, temperature distribution, and material non-uniformity. The effect is roughly equivalent to shortening of the device length L . According to equation (S7), the peak efficiency is proportional to $1/L^2$ and the bandwidth is inversely proportional to L . Therefore, the measurement would match well with the theory if the effective length of interaction is $\sim 1/3$ of the device length. There is room for one order of magnitude improvement in the conversion efficiency.

2. Quasi-phase-matched condition for this PPLN waveguide

At the quasi-phase matching condition ($\Delta k = 0$), equation (S3) is equivalent to:

$$\Lambda = \frac{2\pi}{\beta_{2\omega} - 2\beta_{\omega}} = \frac{\lambda_{2\omega}}{n_{2\omega} - n_{\omega}}. \quad (\text{S8})$$

Once the effective refractive indices n_{ω} and $n_{2\omega}$ are simulated, the relation (S8) allows calculating the poling period Λ as a function of the central working wavelength, as plotted in Fig. S2.

Fig. S2. Poling period calculated with (S8) as a function of the central working wavelength: for a LN thickness of 690 nm (in blue) and 700 nm (in red). Other parameters used in the simulations are the same as those used for the fabricated devices.

It is found that the working wavelength is very sensitive to the poling period. Increasing the period by $0.1 \mu\text{m}$ redshifts the working wavelength by $\sim 30 \text{ nm}$. In addition, the working wavelength is also strongly dependent on the refractive index of the waveguide mode, which depends on the refractive index of the material and is very sensitive to the waveguide geometry. A small perturbation due to fabrication accuracy can result in a large change of working wavelength. Indeed, as shown in Fig. S2, only 10 nm LN thickness difference corresponds to $\sim 20 \text{ nm}$ working wavelength shift. It is therefore highly likely that the non-uniformity of the waveguide geometry is the origin of the decrease in normalized efficiency and the broadening of the bandwidth.

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