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QUANTITATIVE MODEL FOR HIGH POWER OPTICAL PARAMETRIC FLUORESCENCE IN TI:PPLN CHANNEL WAVEGUIDES

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ABSTRACT

Theoretical calculations of high power parametric fluorescence with a good agreement to the experiment in the low depletion case are presented. The high power fluorescence results in a broad fluorescence spectrum. A strong back conversion to the pump reduces the conversion efficiency and leads to a incoherent broadened pump. The back conversion bandwidth depends on the group velocities of the pump, signal and idler wave, respectively.

KEYWORDS

nonlinear optics, optical parametric fluorescence

INTRODUCTION

Optical parametric fluorescence (OPF) was predicted in 1961 [1] and demonstrated in bulk material 1967 [2]. Nowadays new technologies like low loss waveguides and periodically poling provide new possibilities to increase the nonlinear interaction strength by factors of magnitude. For example, high power fluorescence with strong pump depletion could be achieved in bulk material 1997 [4] and in proton exchanged lithium niobate waveguides in 2004 [5]. In both cases a saturation of the conversion efficiency was observed. For example, in the first case the maximal conversion efficiency was 38 % decreasing with increasing pump power. However, resent quantitative models did not take into account pump depletion [3],[8].

In this contribution we present at the first time a theoretical model for the quantitative calculation of high power optical parametric fluorescence. The high power conversion process saturates and a broad incoherent fluorescence spectrum is generated. In the low power regime the modelling results fit well with the experimental ones.

THEORETICAL MODEL

The origin of OPF can only be understood quantum mechanically. Several authors developed a model to describe OPF in nonlinear crystals [1,2]. The classical approach can be used to describe the amplification of this spontaneous process [3]. A coherent pump is assumed and a random phase approach of signal and idler is used to seed the well known time domain equations to model qualitatively high power QPF in a proton exchanged lithium niobate waveguide [4]. In our approach we switch to the frequency domain to seed the classically described down conversion process with a spectral energy density resulting from one spontaneous pump photon scattering per each black body mode. Taking into account that round trip time T_R and longitudinal black body mode separation $\Delta\omega$ are connected via $T_R \cdot \Delta\omega = 2\pi$ the seeding spectral power density can be written as:

$$\frac{\partial P}{\partial \omega} = \hbar \frac{\omega}{2\pi} \quad . \tag{1}$$

In the time domain the time dependent wave power can be interpreted as an energy density. Clearly power and energy are connected via

$$P = \frac{\partial E}{\partial t} \propto \left| \hat{a}(t) \right|^2 \tag{2}$$

$\hat{a}(t)$ is the time dependent amplitude. Similarly the frequency domain amplitudes $a(\omega)$ determine a spectral energy density. In the case of cw operation the spectral amplitude is proportional to the width of the finite computing time domain T_D. From this follows that in the case of cw interaction the amplitudes in the frequency domain are directly proportional to T_D. Finally we can write the spectral energy density as

$$\frac{\partial E}{\partial \omega} = \hbar \frac{\omega}{2\pi} T_D \cdot \tag{3}$$

Starting with the broadband energy density as given in (3) the evolution of OPF in the nonlinear waveguide is analyzed by a classical approach using coupled mode theory in the frequency domain [7]. The corresponding equations are

$$\left\{\frac{\partial}{\partial z}+\frac{\alpha_p}{2}+i\big(\beta(\omega)-\beta(\omega_p)\big)\right\} a_p(z,\omega-\omega_p) = -i\frac{2}{\pi}\kappa\int d\omega\, a_s(z,\omega'-\omega_p)\, a_i(z,\omega-\omega'-\omega_i)$$
$$\left\{\frac{\partial}{\partial z}+\frac{\alpha_s}{2}+i\big(\beta(\omega)-\beta(\omega_s)\big)\right\} a_s(z,\omega-\omega_s) = -i\frac{2}{\pi}\kappa\int d\omega\, a_p(z,\omega'-\omega_p)\, a_i^*(z,-\omega+\omega'-\omega_i) \qquad (4)$$
$$\left\{\frac{\partial}{\partial z}+\frac{\alpha_i}{2}+i\big(\beta(\omega)-\beta(\omega_i)\big)\right\} a_i(z,\omega-\omega_i) = -i\frac{2}{\pi}\kappa\int d\omega\, a_p(z,\omega'-\omega_p)\, a_s^*(z,-\omega+\omega'-\omega_s)$$

p, s and i denote pump, signal and idler, respectively. Scattering losses α and full waveguide dispersion $\beta(\omega)$ are taken into account. The coupling coefficient κ depends on the nonlinear coefficient d_{33} of $LiNbO_3$ and on the mode overlap of pump, signal and idler. It is assumed that the mode overlap is constant over the whole spectrum. Considered quasi phase matching is taken into account by choosing a corresponding period Λ of the ferroelectric grating structure:

$$\Lambda = \frac{2\pi}{\left|\beta(\omega_p)-\beta(\omega_s)-\beta(\omega_i)\right|}\,. \qquad (5)$$

The set of equations (4) can be solved via a fast fourier transform split step method. In the low pump power regime, when pump depletion and back conversion can be neglected, the upper equations decouple and the spectral energy density of the fluorescence is independent on the random phase distribution of the seeding spectrum. In the high pump power regime the situation is different. Back conversion by sum frequency mixing plays a significant role and the fluorescence spectra are highly dependent on the arbitrarily chosen phase distribution of the seeding spectrum. Therefore, the results of up to 250 calculations with independent chosen arbitrary phase distribution of the input seeding spectrum are averaged. In this case the total fluorescence power is given by

$$P^{total}(z=L) = \left(1+\frac{\lambda_s}{\lambda_i}\right)\frac{1}{T_D}\int d\omega \left(\frac{\partial E^{signal}(z=L)}{\partial\omega}\right)^{average}. \qquad (6)$$

λ_s and λ_i are the centre wavelength of the signal and idler spectra, respectively. L is the length of the waveguide.

RESULTS AND DISCUSSION

The left diagram in Fig. 1 shows the calculated total OPF output power in a range covering 12 orders of magnitude (!) together with some experimental results as function of the coupled pump power in a double

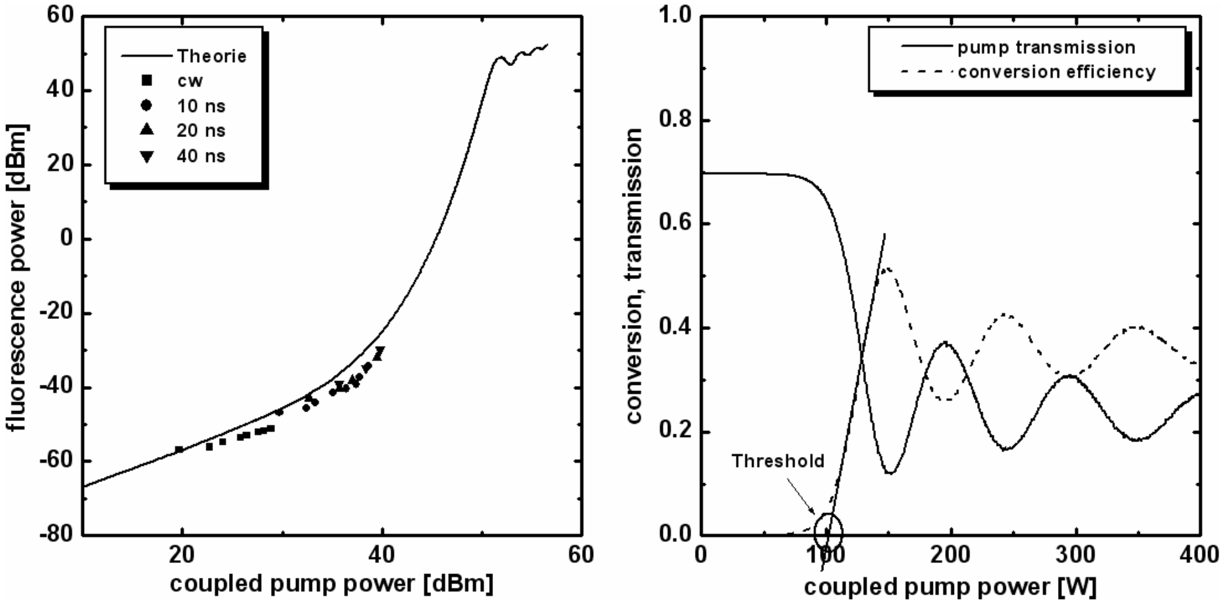

Fig. 1: (left) Calculated and measured fluorescence power (λ_s = 3400 nm, λ_i = 2849 nm) versus coupled pump power (λ_p = 1550 nm). (right) Pump transmission and conversion efficiency as a function of coupled pump power at the same operating point.

logarithmic plot. In the low power regime the fluorescence power depends linearly on the coupled pump power. At higher pump power levels the dependence becomes strongly nonlinear before pump depletion sets in with an oscillatory transition to a nearly linear response in the high depletion regime. The experiment was performed in a 94 mm long periodically poled Ti:$LiNbO_3$ channel waveguide to generate OPF in the mid infrared at λ_s = 3400 nm and λ_i = 2849 nm with a pump at λ_p = 1550 nm [9]. Pulses of a width of 10 ns - 40 ns with a repetition rate of 1 MHz have been used. The agreement of theoretical and experimental results at pump peak power levels up to 10 W is satisfactory.

The right diagram shows the conversion efficiency and the transmitted pump power as function of the coupled pump power in a linear plot. Transmission and conversion are defined as $P(L)/P_{pump}(0)$ with P(L) as pump and fluorescence power, respectively. At low pump levels the pump transmission of about 0.7 is mainly determined by the waveguide scattering losses; pump depletion due to OPF-generation can be neglected. This results in a nearly constant transmission for power levels lower then 60 W. Stronger OPF-generation sets in at higher pump power levels. A "threshold" can be defined as shown in the figure as the intersection point of the tangent on the conversion efficiency and the abscissa. We determined in this way a threshold of 100 W coupled pump power. The maximum achieved conversion efficiency is 0.51 or – 2.9 dB at a pump power level of 150 W.

Fig. 2 is a schematic sketch of the back conversion mechanism. In the first step a high gain down conversion occurs and generates a high power incoherent fluorescence. The amount of back conversion and therewith the maximum conversion efficiency is mainly determined by the bandwidth of the back conversion process. If we assume phase matching for $\omega_{p,}$ ω_s and ω_i and if we take into account $\Delta\omega_p = \Delta\omega_s + \Delta\omega_I$ phase matching can be found at $\omega_p+\Delta\omega_p$, $\omega_s+\Delta\omega_s$ and $\omega_i+\Delta\omega_p-\Delta\omega_s$ fulfilling

$$\Delta\omega_p = \frac{n_s^g - n_i^g}{n_p^g - n_i^g}\Delta\omega_s = a\Delta\omega_s \cdot \tag{7}$$

n^g are the group indices of pump, signal and idler, respectively. a is defined as the ration of the group velocity mismatches. This relation follows directly from the variation of the phase matching condition. a can be understood as the slope of a linear function. Accordingly the back conversion bandwidth is determined by the group velocity mismatch (GVM). The group velocity in Ti:$LiNbO_3$ channel waveguides has a maximum at 1900 nm. The special case in our situation is that the group velocity of the idler is closer to that of the pump then to the signals. For the chosen set of wavelengths we found $a \approx -2$. A change of the pump frequency can be compensated by a smaller change of the signal frequency to fulfill the phase matching condition. This is the physical origin of the broad back conversion bandwidth. The situation in the near infrared is different. For λ_p = 780 nm, λ_s = 1550 nm and λ_i = 1570 nm group velocity of signal and idler is very close together and far from the pump group velocity. We found $a \approx 5.7 \cdot 10^{-3}$ and a strongly reduced back conversion bandwidth.

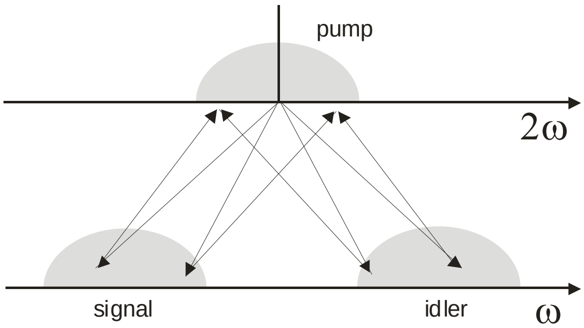

Fig. 2: Mechanism of incoherent nonlinear broadening.

The spectrum of the generated signal fluorescence is shown in Fig. 3. A similar spectrum can be observed at the idler wavelength around 2849 nm. In the low gain regime (1 W coupled pump power) the fluorescence spectrum shape is identical to the acceptance bandwidth of the low gain difference frequency generation. This bandwidth broadens for higher pump power and back conversion set in if the coherent part of the pump is depleted and the pump transmission is determined by the broad incoherent background following from the back conversion process.

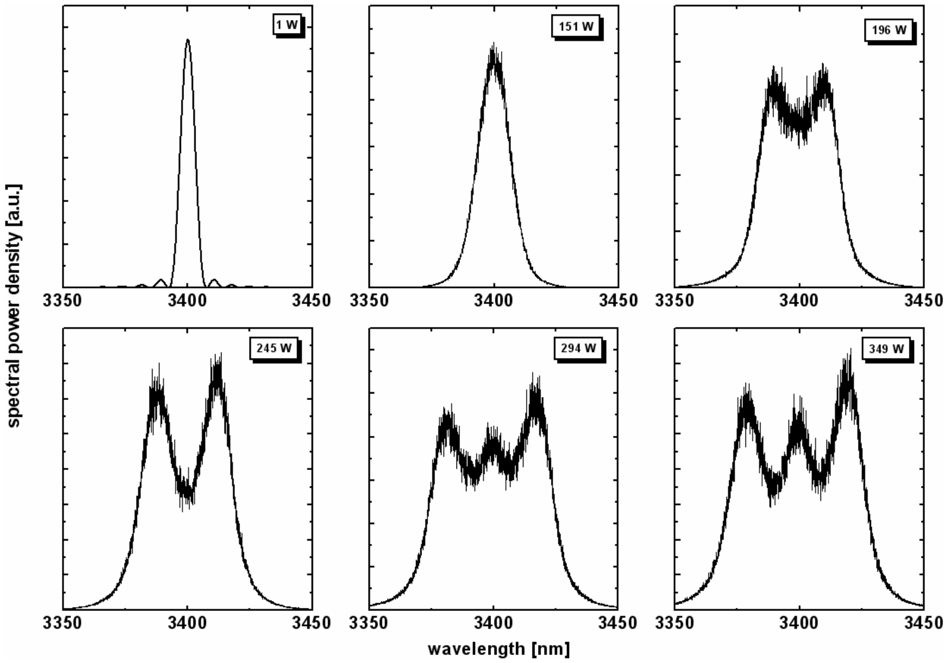

Fig. 3: Fluorescence spectra for different pump levels in arbitrary units of spectral power density.

CONCLUSION

We have presented a theoretical model which allows a quantitative calculation of high power optical parametric fluorescence with strong back conversion. High power fluorescence in Ti:$LiNbO_3$ has been analysed. In the low power regime it fits good to the experiment. It is shown that high power fluorescence results in a broad incoherent fluorescence spectrum. Due to nonlinear back conversion this broad high power incoherent fluorescence spectrum results in a incoherent broadening of the pump. The back conversion bandwidth depends directly on the group velocity mismatches of pump, signal and idler, respectively.

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