Quasiphasematched concurrent nonlinearities in periodically poled KTiOPO$_4$ for quantum computing over the optical frequency comb

Matthew Pysher, Alon Bahabad, Peng Peng, Ady Arie, and Olivier Pfister

1 Department of Physics, University of Virginia, 382 McCormick Road, Charlottesville, VA 22904-4714, USA
2 Department of Physics and JILA, University of Colorado at Boulder and NIST, Boulder, Colorado 80309, USA
3 Department of Physical Electronics, Fleischman Faculty of Engineering, Tel Aviv University, Ramat Aviv 69978, Israel

*Corresponding author: opfister@virginia.edu

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Quantum computing is an exciting field driven by the promise of exponential speedup of a priori arduous computational processes such as integer factoring [1, 2]. Most proposals for experimentally implementing quantum computing call for the use of two-state quantum systems, or qubits [3]. However, a quantum computer could very well use continuous quantum variables [4, 5], such as position and momentum, or the quadrature amplitude operators of the quantized field [6–8]. Recently, some of us have proposed a new and extremely scalable method for building a quantum register by use of the set of quantum harmonic oscillators (“qumodes”) defined by a single optical resonator [9, 10]. In this proposal, the quantum correlations (entanglement) necessary for quantum computing will be implemented by a nonlinear medium placed inside the cavity, thereby realizing a sophisticated optical parametric oscillator (OPO). The sophistication stems from the fact that three different second-order nonlinear interactions must be simultaneously phasematched over the same set of cavity modes, i.e. must be concurrent. These interactions are parametric downconversion ($\lambda/2 \rightarrow \lambda$) of ZZZ (“type-0”), ZYY (type-I), and YYZ/YZY (type-II) second harmonic generation of 780 nm light from a 1560 nm pump beam in a single, multigrating, periodically poled KTiOPO$_4$ crystal. The resulting nonlinear medium is the key component for making a scalable quantum computer over the optical frequency comb of a single optical parametric oscillator. © 2011 Optical Society of America

We report the successful design and experimental implementation of three coincident nonlinear interactions, namely ZZZ (“type-0”), ZYY (type-I), and YYZ/YZY (type-II) second harmonic generation of 780 nm light from a 1560 nm pump beam in a single, multigrating, periodically poled KTiOPO$_4$ crystal. The resulting nonlinear medium is the key component for making a scalable quantum computer over the optical frequency comb of a single optical parametric oscillator. © 2011 Optical Society of America

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Quantum computing is an exciting field driven by the promise of exponential speedup of a priori arduous computational processes such as integer factoring [1, 2]. Most proposals for experimentally implementing quantum computing call for the use of two-state quantum systems, or qubits [3]. However, a quantum computer could very well use continuous quantum variables [4, 5], such as position and momentum, or the quadrature amplitude operators of the quantized field [6–8]. Recently, some of us have proposed a new and extremely scalable method for building a quantum register by use of the set of quantum harmonic oscillators (“qumodes”) defined by a single optical resonator [9, 10]. In this proposal, the quantum correlations (entanglement) necessary for quantum computing will be implemented by a nonlinear medium placed inside the cavity, thereby realizing a sophisticated optical parametric oscillator (OPO). The sophistication stems from the fact that three different second-order nonlinear interactions must be simultaneously phasematched over the same set of cavity modes, i.e. must be concurrent. These interactions are parametric downconversion ($\lambda/2 \rightarrow \lambda$) of ZZZ (“type-0”), ZYY (type-I), and YYZ/YZY (type-II), where the first letter denotes the polarization of the pump field and the last two letters denote the polarization of the signal (entangled) beams. In previous work [11], we demonstrated the simultaneous quasi-phasematching (QPM) of this set of interactions at room temperature for $\lambda = 1490$ nm in periodically poled KTiOPO$_4$ (PPKTP) with a single period of 45.65 $\mu$m. This was a serendipitous discovery that relied upon a weak seventh-order QPM of the YZY interaction (even though the final signal turned out to be much larger). Despite this result, designing concurrent nonlinear interactions remained difficult because the precision on the Sellmeier coefficients, as well known as they are, was still not high enough, in particular for $n_r$.

In this Letter, we use Fourier engineering [12, 13] to achieve and demonstrate a concurrent design with low-order, hence efficient, QPM at $\lambda = 1560$ nm, close to the loss minimum of silica optical fibers. Recent advances in squeezing at and around this wavelength also make it a reasonable choice [14, 15]. This 1560 nm design required the use of three different poling periods. Two early iterations used published Sellmeier equations [16–18]. In these initial versions, the ZZZ and ZYY QPM peaks overlapped well at 1560 nm at room temperature but the YZY interaction was quasi-phasematched for 1560 nm between average temperatures of 248.7°C (for a designed phase mismatch of $1.398 \times 10^5 \text{ m}^{-1}$ at room temperature) and 300.1°C (for a designed phase mismatch of $1.410 \times 10^5 \text{ m}^{-1}$ at room temperature). From these two measurements, and considering the corrections owing to the temperature expansion of the crystal [18], we deduced that the phase mismatch value of the YZY process shifts with temperature with a slope of $22.34 \text{ m}^{-1}/\text{K}$. This enabled us to predict the expected phase mismatch of the YZY interaction at 40°C to be $1.348 \times 10^5 \text{ m}^{-1}$. However, owing to the uncertainty of this linear slope correction, we adopted a multi-section design for the crystal. The 10 mm × 6mm × 1 mm crystal was divided into two sections, lengthwise.

The first section, of length 5mm, was a Fourier-engineered ZZZ/ZYY concurrence grating crystal created using the generalized dual grid method [13] which was previously shown to create nonlinear photonic quasicrystals whose reciprocal lattices contain an arbitrary set of desired wave vectors [19, 20]. With corresponding mismatch values of $\Delta k_{ZZZ} = 2.510 \times 10^5 \text{ m}^{-1}$ and $\Delta k_{ZYY} = 9.061 \times 10^5 \text{ m}^{-1}$, we designed a quasiperiodic structure with reciprocal base vectors $k_1 = \Delta k_{ZZZ} + \Delta k_{ZYY}$ and $k_2 = \Delta k_{ZYY}$ such that the desired orders for phase matching the two processes are $(1, -1)$ and $(0, 1)$ in this basis. Feeding these values into the algorithm of the dual grid method, we got the two tiling vectors of the quasiperiodic structure to be of length 3.37 $\mu$m and 2.64 $\mu$m. The duty cycles used for the two build-
ing blocks of the structure were 0% and 100% respectively. This means that the 3.37 \( \mu m \) building block is fabricated with a positive value of the nonlinear susceptibility, and the 2.64 \( \mu m \) building block with a negative value. The Fourier coefficients given by this structure for the ZZZ and ZYY processes are 0.112 and 0.3855 respectively. The reciprocal basis vectors and the duty cycles of the building blocks were chosen to both maximize the Fourier coefficients and to make the product of the Fourier coefficient and the material nonlinear coupling coefficient of the two processes approximately the same. We refer the interested reader to a detailed account of using the dual grid method for the design of quasiperiodic nonlinear photonic crystals able to phase match several different processes simultaneously [19].

The second section of the crystal was composed of five parallel, 1 mm wide, gratings, of respective periods 45.9, 46.3, 46.7, 47.2, and 47.7 \( \mu m \) in an attempt to correctly sample the wider range of QPM variation for the YZY interaction. These periods are centered around the interpolated phase mismatch value of \( 1.348 \times 10^5 \text{m}^{-1} = \frac{2\pi}{46.6} \mu m \) that was obtained from the measurements with the two previous samples. The ZZZ/ZYY QPM section was as wide as the crystal and overlapped with all YZY channels.

The experimental study used second-harmonic generation (SHG) with the setup shown in Fig. 1. The input light was filtered out by a pair of long-pass filters that reflected approximately 30\% of light in the 715–900 nm wavelength range while passing over 85\% of light between 985 and 2000 nm. Before reaching the detector, the SHG light passed through a half-waveplate and polarizing beam splitter combination, which allowed us to choose the SHG polarization to be detected. Any residual fundamental light was filtered by the very low detection efficiency of our silicon photodiode at that wavelength. The detected light was measured by taking the average of ten measurements on the signal analyzer and recording the signal at 450 Hz. The efficiency of the various nonlinear interactions was controlled by adjusting both the crystal temperature and the wavelength of the input beam. The desired YZY poling period fell in between the 45.9 and 46.3 \( \mu m \) periods that were used to create our first two YZY channels. The other three YZY channels did not yield a significant SHG signal within the temperature range obtainable by our thermoelectric controller. Figure 2 shows the temperature dependence of the YZY SHG signal for each of the 5 channels. The poling periods used from left to right were 45.9, 46.3, 46.7, 47.2, and 47.7 \( \mu m \).

\[ \text{Fig. 1. Experimental setup.} \]

\[ \text{Fig. 2. Temperature dependence of the YZY SHG signal for each of the 5 channels.} \]

\[ \text{Fig. 3. Triply concurrent SHG as a function of temperature at 1560 nm in the 46.3 \( \mu m \)-period YZY channel.} \]

It appears that the 45.9 \( \mu m \) period corresponds to a QPM temperature larger than 65\°C (which was the limit of our oven), while the 46.3 \( \mu m \) period is optimized just below 15\°C. Despite the fact that none of our YZY channels used the exact poling period needed to put the SHG peak at 1560 nm at 40 degrees, the large temperature acceptance bandwidth of YZY phase-matching (approximately 30\° C \times cm) yielded good overlap with the ZZZ
and ZYY interactions, as can be seen from Fig. 3.

Figure 4 shows results obtained using the ZZY channel with the 46.3 μm period, at a temperature of 37°C. A fit of the data shows the ZYY peak to occur at exactly 1560 nm at this temperature, while the ZZZ peak occurs at 1560.2 nm. The location of the beam waist in the crystal was adjusted so that the YZY SHG output matched that of ZZZ. When the waist was moved to maximize YZY, the YZY near-peak efficiency (at 15°C, see Fig. 3) became approximately double that of the peak ZZZ efficiency at 37°C. Using the aforementioned Fourier coefficients and the values $d_{33} = 15.4$ pm/V and $d_{32} = d_{24} = 3.75$ pm/V [21], we obtain a YZY to ZZZ peak-efficiency ratio of $[(3.75 \times 0.3855)/(15.4 \times 0.112)]^2 = 2.09/2.97 = 0.70$, consistent with the experimental results of Figs. 3, 4. For the YZY to ZZZ peak-efficiency ratio, we obtain $[(3.75 \times 2/\pi)/(15.4 \times 0.112)]^2 = 5.70/2.97 = 1.92$, again consistent with our experiment. This therefore confirms the values of Ref. 21. Note that the initial design used the different values $d_{33} = 13.7$ pm/V and $d_{32} = 5$ pm/V, which is why the YZY interaction ends up weaker than ZZZ, but this can clearly be remedied.

In conclusion, we have designed and experimentally demonstrated a PPKTP crystal with three concurrent phase-matchings at 1560 nm. The knowledge gained about the YZY QPM period in this work can now be applied to generating a single Fourier-engineered grating for all three processes [13]. Having a triply concurrent crystal made with a single Fourier-engineered grating gives several advantages over a crystal containing three separate polings. In particular, the single grating would allow the crystal to be used in single-pass operations, such as those using a nonlinear waveguide, rather than an optical cavity. For example, just using the simultaneous ZZZ and ZYY phase-matchings in the Fourier-engineered crystal of this work could yield a useful source of collinear polarization-entangled photon pairs. Note that this method could also be used to make a crystal with four concurrent phase matchings in other materials, such as LiNbO$_3$ and LiTaO$_3$. Last but not least, and most importantly here, the crystal in this study represents the key component in the implementation of quantum computing over the optical frequency comb [9, 10], which is, in theory, extremely scalable.

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