Generation of microwave radiation by nonlinear interaction of a high-power, high-repetition rate, 1064 nm laser in KTiOPO₄ crystals

A. F. Borghesani,¹,² C. Braggio,²,³ and G. Carugno²
¹CNISM unit, Department of Physics & Astronomy, University of Padua, 35131 Padua, Italy
²Istituto Nazionale di Fisica Nucleare, Sezione di Padova, 35131 Padua, Italy
³Department of Physics & Astronomy, University of Padua, 35131 Padua, Italy
*Corresponding author: armandofrancesco.borghesani@unipd.it

Received July 4, 2013; revised September 12, 2013; accepted October 14, 2013; posted October 15, 2013 (Doc. ID 193224); published October 31, 2013

We report measurements of microwave (RF) generation in the centimeter band accomplished by irradiating a nonlinear KTiOPO₄ crystal with a home-made, infrared laser at 1064 nm as a result of optical rectification. The laser delivers pulse trains of duration up to 1 μs. Each train consists of several high-intensity pulses at an adjustable repetition rate of approximately 4.6 GHz. The duration of the generated RF pulses is determined by that of the pulse trains. We have investigated both microwave- and second harmonic generation as a function of the laser intensity and of the orientation of the laser polarization with respect to the crystallographic axes of KTP. © 2013 Optical Society of America

OCIS codes: (350.4010) Microwaves; (160.4330) Nonlinear optical materials; (160.2100) Electro-optical materials; (140.4050) Mode-locked lasers.

http://dx.doi.org/10.1364/OL.38.004465

Optical heterodyning is at the basis of several techniques to produce microwave signals [1–3]. Two adjacent laser lines are brought to beat in a nonlinear crystal to generate signals at the difference frequency, which lies in the microwave domain. Authors have demonstrated generation of beat notes at frequencies from a few GHz up to the THz band [4,5].

Optoelectronic oscillators have also been developed that generate spectrally pure microwave signals by modulating continuous laser light in interferometric devices [6], whose performance is limited by the bandwidth of the state-of-the-art photodetectors [7,8].

In this Letter, we report about a novel technique of microwave and mm wave signal photonic generation. The method is demonstrated at ≈3.7 GHz but can be extended up to a few hundred GHz [9,10]. It is based on the fast response of a second-order nonlinear crystal to a pulse train delivered by a high-intensity, mode-locked laser system, whose repetition rate f is in the RF domain. The irradiation of such a crystal with a train of short laser pulses produces a time-dependent polarization in the crystal as a consequence of optical rectification (OR) [11]. This process gives origin to the emission of microwave radiation that can be transferred to any receivers, either a cavity or a waveguide, without the bandwidth limitation of photodetection. OR has also been used to produce subpicosecond THz pulses by using ultrashort laser pulses in a number of nonlinear crystals [12,13].

We used a KTiOPO₄ (KTP) crystal because its noncentrosymmetric, orthorombic crystal structure belonging to the 2 mm point symmetry group [14] endows it with a strong second-order nonlinearity. Its electro-optic coefficients are well known [15–17] and it is, thus, very well suited to characterize our technique to produce RF radiation.

In Fig. 1 a scheme of the experimental setup is shown. The KTP crystal used (EKSMA Optics) is a parallelepiped 4 mm × 4 mm × 10 mm in size whose long axis is aligned in the direction z of the laser propagation. The crystal is cut in a way that its optical axis z′ forms an angle β ≈ 59° with z, necessary for phase matching purposes in a previous experiment. It is mounted in the center of a rectangular RF cavity (C) designed so as to sustain a TE₉₁₁ mode. Its resonance frequency can be tuned to the laser pulses repetition rate that can be varied in the range 4.4–4.7 GHz. The crystal can be rotated about the z axis to maximize the coupling of the RF emission with the cavity mode. The quality factor of the loaded cavity is Q ≈ 10⁶. A critically coupled antenna (A) is used to pick up the RF signal that is directly fed to the 50 Ω input of the oscilloscope (S).

The infrared (λ = 1064 nm) laser (L), described elsewhere [18], is set to deliver one 400 ns or more long-pulse train every second. The pulse width is τ ≈ 12 ps and each train contains ≈2000 of them, the pulse repetition rate being set at f = 4.6 GHz. In this way, a restricted-band frequency comb [19] is generated with mode frequencies...
rotated by the $\lambda/2$ plate. The results are displayed in Fig. (3). $V_{RF}$ shows a marked four-fold periodicity and can be accurately fitted to the following form:

$$V_{RF} = V_0 + V_4 \cos[4(\theta - \gamma_4)],$$

with $V_0 = 80.9$ mV, $V_4 = 33.9$ mV, $\gamma_4 = 69^\circ$ has no physical relevance.

As the antenna signal is proportional to the first time derivative of the microwave field, the angular dependence of the nonlinear polarization can be calculated from $d_{ijk}$. The low-frequency crystal polarization $P(t)$ closely follows the envelope $|E_{RF}^0(t)|^2$ of the electric field $E_{RF}^0(t) = E_{RF}^0 \cos \omega t$ of the optical pulse train [13], where $\omega = 2\pi f_{RF}$ is the angular frequency of the laser. The Fourier spectrum of $P(t)$ contains the fundamental harmonic at the microwave frequency $f$ plus several higher-order harmonics. The resonant cavity acts as narrow bandpass filter that picks out the amplitude $P_0$ of the fundamental that can be written in the frame of reference of the crystallographic axes $(x', y', z')$ as

$$P_{0i} = A d_{ijk}^0 E_{o j k}^0 \quad (i, j, k = x', y', z').$$

The convention of summation over repeated indices is observed. The constant $A$ depends on the actual shape of the individual pulses in the train. $d_{ijk}^0$ are the elements of the nonlinear susceptibility tensor and the prime means that they are referred to the crystallographic system. For a KTP crystal, only five of its elements are non-null [14]. The crystallographic system is rotated with respect to the laboratory frame of reference so that the crystal axis $z'$ forms an angle $\beta$ with the laser propagation direction $z$. Thus, the polarization components in Eq. (2) must be expressed in the laboratory frame.

The laser light is linearly polarized with components $E_{ox}^0 = E_{oy}^0 = E_0$ in the laboratory. A rotation of the $\lambda/2$ plate by an angle $\theta$ rotates the laser polarization by $2\theta$. Thus, the components of the field incident on the entrance face of the crystal are $E_{ox} = E_0 \cos 2\theta$ and $E_{oy} = E_0 \sin 2\theta$.

The elements of the nonlinear second-order susceptibility tensor for OR, $d_{ijk}^0$, and for SHG, $d_{ijk}^{2o}$, could in principle be different. However, we argue that they are nearly the same. In fact, as in our case there is only one strong

$$f_L \pm m f_o,$$ where $f_L = c/\lambda \approx 2.82 \times 10^{14}$ s$^{-1}$ is the laser frequency. Because of the Gaussian shape and duration of the individual pulses, the highest overtone of non-negligible amplitude has index $m_{\text{max}} \approx 20$, so that $m_{\text{max}} f_o \ll f_L$, and all the frequencies in the laser spectrum are in the optical region [20].

The maximum laser intensity value is limited to $I \approx 130$ MW/cm$^2$ in order to keep $I$ well below the damage threshold (>500 MW/cm$^2$ for 10 ns long pulses). $I$ can be reduced by inserting calibrated neutral density filters in the laser path. We note that the lower limit to the laser intensity is set by the requirement that it forces the nonlinear response of the crystal. We experimentally observed microwave generation by KTP with $I$ as low as 0.2 MW/cm$^2$.

The laser polarization can be rotated relative to the crystal axes by means of a $\lambda/2$ wave plate mounted on a rotating goniometer. The laser beam has an ellipsoidal Gaussian profile with semi-axes $a \approx 1.5$ mm and $b \approx 1.8$ mm, respectively, and is fully projected onto the antireflection coated, entrance face $(x, y)$ of the crystal. The light exiting the crystal output face contains the contribution due to the second harmonic generation (SHG) and to the pump laser. The SH is picked out by a combination of a harmonics separator (HS) and a band-pass filter $(F)$ and is measured by a photodiode (PD) whose output voltage $V_G$ is proportional to its intensity. A bolometer $(B)$ is used to monitor the laser stability.

In Fig. (2) we show the amplitude $V_{RF}$ of the microwave signal and the SH intensity $V_G$ as a function of the laser intensity $I$ for a fixed position of the $\lambda/2$ plate. In our experiment, the efficiency of the SHG is of a few percent. The presence of SH is a clear sign of a quadratic nonlinear effect. Actually, $V_G \propto I^2$, the proportionality constant depending on the second-order susceptibility tensor for the mixing of two identical frequencies $d_{ijk}^{2o}$. By contrast, the antenna signal is proportional to the time derivative of the microwave polarization field that depends on the quasi-static polarization induced by OR. Thus, the amplitude of the RF signal is directly proportional to the laser intensity, $V_{RF} \propto I$, the proportionality constant depending on $d_{ijk}^0$. The experimental data confirm these expectations.

To further verify that the microwave radiation is produced by OR, we measured the dependence of $V_{RF}$ on the angle $\theta$ by which the direction of the laser polarization is
laser source, the nonlinear, quadratic, electro-optic tensor is of electronic origin [20]. In the case of resonant mixing, if the driving frequencies are in the optical domain, whereas the difference frequency is below any lattice resonances, there is no contribution of the lattice to $d_{jk}^{\text{dielectric}}$ [21]. Moreover, the tensor elements can be written as $d_{jk}^{\text{dielectric}} \propto \chi^{(2)}_e(\omega_2 \pm \omega_1)\chi^{(2)}(\omega_1)\chi^{(2)}(\omega_2)$, where the $\chi^{(2)}_e$'s are the linear electronic susceptibilities. They are related to the dielectric constant $\epsilon$ of the material and, thus, to the refractive index [22]. It is reported that the static dielectric constants $\epsilon^{(2)}(\omega)$ do not differ by more than a few percent from the square of the refractive indices at optic frequencies $n_g^2(\omega)$ [23]. For these reasons, we assume $d_{jk}^{(0)} \approx d_{jk}^{(2\omega)}$ and drop either superscripts.

The effective, nonvanishing elements of the nonlinear second-order susceptibility tensor are thus expressed in the laboratory frame as

\begin{align*}
    d_{15} &= 2bd_{15} \cos 2\theta \sin 2\theta, \\
    d_{24} &= 2ab\epsilon_0^2 \sin^2 2\theta, \\
    d_{31} &= d_{31} \cos^2 2\theta, \\
    d_{32} &= d_{32} \cos^2 2\theta, \\
    d_{33} &= d_{33} b^2 \sin^2 2\theta,
\end{align*}

in which $a = \cos \beta$ and $b = \sin \beta$.

$V_{RF}$ is now given by the projection of the induced low-frequency polarization onto the direction of the electromagnetic mode of the cavity. It is easy to show that

\begin{equation}
    V_{RF} = B E_0^2 g(\theta) = C I g(\theta),
\end{equation}

where $I = c e_0 E_0^2$ is the laser intensity, $e_0$ is the vacuum permittivity, $B = B(f, \omega)$ and $C = B/c e_0$ are constant at fixed RF frequency and laser pulsation $\omega$. $B$ accounts for many parameters, such as effective interaction volume, antenna efficiency, and so on. The function $g(\theta)$ is given by

\begin{equation}
    g(\theta) = g_x d_{15} + g_y d_{24} + g_z (d_{31} + d_{32} + d_{33}).
\end{equation}

The direction cosines $g_x$, $g_y$, and $g_z$ of the induced, nonlinear polarization field relative to the cavity mode polarization are unknown and are obtained by a fit to the experimental data.

Equation (4) explains both the results for $V_{RF}$ in Figs. (2) and (3). The $V_{RF}$ data in Fig. (2) are measured at fixed angle $\theta = \theta_0$. So, $g(\theta)$ is a constant and $V_{RF}$ turns out to be directly proportional to the laser intensity $I$.

The data shown in Fig. (3) are obtained at constant $I$, so they display the behavior of $g(\theta)$. It can be shown that by expanding the trigonometric functions, Eq. (5) can be cast in the form given by Eq. (1). By inserting the known values of the nonlinear electro-optic coefficient of KTP [17], the values of the direction cosines can be determined by comparison with the fit parameters in Eq. (1). If $g_x = -3.72 \times 10^{-2}$, $g_y = -0.911$, and $g_z = 0.411$ are chosen, Eq. (5) accurately fits the experimental data.

A further verification of the validity of Eq. (1) can be obtained by measuring $V_{RF}$ as a function of the laser intensity $I$ for several angular positions of the $\lambda/2$ plate.

From plots similar to Fig. (1), we determined the slope of $V_{RF}$ versus $I$ for some values of $\theta$. The slope values are reported in Fig. (4). According to Eq. (4), the slope is proportional to $g(\theta)$ and the experimental results confirm this expectation.

SHG is also a consequence of the quadratic nonlinearity of the medium polarizability [14]. In Fig. (2) we have shown that the SH intensity quadratically depends on $I$. In Fig. (5) the dependence of the SH intensity on the direction $\theta$ of the pump laser polarization for $I \approx 74$ MW/cm$^2$ is shown. The data show an eight-fold periodicity modulated by one that is four-fold and are fitted to a function of the form

\begin{equation}
    V_G = V_0 + V_8 \cos(8(\theta - \gamma_8)) + V_4 \cos(4(\theta - \gamma_4)),
\end{equation}

with $V_0 = 190.8$ mV, $V_8 = 112.2$ mV, and $V_4 = 21.7$ mV. $\gamma_8 = 46.6^\circ$ and $\gamma_4 = 67.3^\circ$ have no physical relevance.

The dependence of $V_G$ on the direction of the laser polarization is computed in a way similar to $V_{RF}$. By recalling that $V_G$ is proportional to the square of the second time derivative of the induced nonlinear polarization and by recalling that the SH is nearly copropagating with the laser along $z$, $V_G$ can be written as

\begin{equation}
    V_G = D \omega^4 I^2 q(\theta),
\end{equation}

with $q(\theta) = q_x d_{15} + q_y d_{24} + q_z (d_{31} + d_{32} + d_{33})$. The constant $D$ depends on the interaction volume, on the
photodetection efficiency, and so on. $q_x$, $q_y$, and $q_z$ give the orientation of the crystal relative to the propagation axis accounting for a possible nonperfect alignment of the geometrical $z$ axis of the crystal with respect to the laser propagation direction. The choice $q_x = 0.162$, $q_y = -0.984$, and $q_z = 0.081$ gives an excellent fit to the data, as displayed as a solid line in Fig. (5).

In this Letter, we have shown that microwave radiation in the centimeter band is optically produced by exploiting the nonlinear polarization properties of KTP crystals. The irradiation of a second-order nonlinear crystal with high-intensity laser pulses at a repetition rate in the microwave domain produces a modulation at the same frequency of OR, which is the source of RF radiation.

The phenomenon we have described could be exploited as a new technique to build flexible RF sources for applications, in which the RF pulse duration and frequency have to be tailored according to specific needs. To this goal, a characterization of such a source, including the determination of the spectral density of the phase noise, may be necessary. In this experiment, the limited duration of the RF pulses prevents its measurement. However, we reasonably expect that in a CW system, this feature is mainly determined by the frequency stability of the optical oscillator [24]. Moreover, the bandwidth of the produced microwave signal is determined by both the pulse train duration and the cavity $Q$ value. This methodology can also be a useful tool to characterize the nonlinear electro-optic coefficients of crystals.

The authors thank E. Berto for technical assistance and acknowledge financial support by Istituto Nazionale di Fisica Nucleare within the MIR experiment.

References
1. T. J. Bridges and S. R. Strnad, Appl. Phys. Lett. 20, 382 (1972).
2. J. Yao, J. Lightwave Technol. 27, 314 (2009).
3. M. H. Khan, H. Shen, Y. Xuan, L. Zhao, S. Xiao, D. E. Leaird, A. M. Weiner, and M. Qi, Nat. Photonics 4, 117 (2010).
4. K. E. Niebuhr, Appl. Phys. Lett. 2, 136 (1963).
5. H. Lengfellner, Opt. Lett. 12, 184 (1987).
6. J. C. Leader, C. E. Larson, and P. A. Treis, J. Appl. Phys. 92, 6505 (2002).
7. A. Neyer and E. Voges, Appl. Phys. Lett. 40, 6 (1982).
8. X. S. Yao and L. Maleki, Opt. Lett. 21, 483 (1996).
9. L. Kainer, R. Paschotta, S. Lecomte, M. Moser, K. J. Weingarten, and U. Keller, IEEE J. Quantum Electron. 38, 1331 (2002).
10. U. Keller, Nature 424, 831 (2003).
11. M. Bass, P. A. Franken, J. F. Ward, and G. Weinreich, Phys. Rev. Lett. 9, 446 (1962).
12. X. C. Zhang, Y. Jin, and X. F. Ma, Appl. Phys. Lett. 61, 2764 (1992).
13. S. Graf, H. Sigg, and W. Bächtold, Appl. Phys. Lett. 76, 2647 (2000).
14. A. Yariv and P. Yeh, Photonics. Optical Electronics in Modern Communications (Oxford, 2007).
15. J. D. Bierlein and C. B. Arweiler, Appl. Phys. Lett. 49, 917 (1986).
16. B. Boulanger, J. P. Fève, G. Marnier, B. Ménagert, X. Cabirol, P. Villeval, and C. Bonnin, J. Opt. Soc. Am. B 11, 750 (1994).
17. M. V. Pack, D. J. Armstrong, and A. V. Smith, Appl. Opt. 43, 3519 (2004).
18. A. Agnesi, C. Braggio, G. Carugno, F. D. Valle, G. Galeazzi, G. Messineo, F. Pirzio, G. Reali, and G. Ruso, Rev. Sci. Instrum. 82, 115107 (2011).
19. S. T. Cundiff and J. Ye, Rev. Mod. Phys. 75, 325 (2003).
20. G. D. Boyd, T. J. Bridges, M. A. Pollack, and E. H. Turner, Phys. Rev. Lett. 26, 387 (1971).
21. C. G. B. Garrett, IEEE J. Quantum Electron. 4, 70 (1968).
22. R. C. Miller, Appl. Phys. Lett. 5, 17 (1964).
23. A. H. Reshak, I. V. Kityk, and S. Auluck, J. Phys. Chem. B 114, 16705 (2010).
24. J. Millo, R. Boudot, M. Lours, Y. P. Bourgeois, A. N. Luiten, Y. L. Coq, Y. Kersaké, and G. Santarelli, Opt. Lett. 34, 3707 (2009).