Laser-induced Microwave Generation with Nonlinear Optical Crystals

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INTRODUCTION

We report about a novel technique of microwave and mm-wave signal photonic generation [1, 2]. The method is demonstrated at approximately 4.6 GHz but can be extended up to a few hundreds GHz. 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 is in the microwave domain. During each pulse of duration \( \tau \) the laser electric field \( E(t) = E_0 \cos \omega t \) induces in the crystal a polarization \( P_{NL}(t) \), resulting from the second order term in a power series expansion of the polarization in terms of the electric field \( E(t) \):

\[
P_{NL}(t) = 2dE_0^2 \cos^2 \omega t = dE_0^2 + dE_0^2 \cos 2\omega t \tag{1}
\]

where \( d \) is the scalar second order nonlinear coefficient and \( \omega \) is the angular frequency of the laser light. The last term in Eq.1 gives rise to the second harmonic light (SHG), whereas the first one, \( P_0 = dE_0^2 \), corresponds to a DC polarization within the crystal, the so-called optical rectification effect (OR). Therefore for each laser pulse a DC signal is produced in the crystal that replicates the laser pulse. Therefore a train of laser pulses corresponds to a time-dependent polarization in the nonlinear material and pulsed microwave radiation is generated, whose Fourier spectrum extends up to the inverse of the single laser pulse duration.

METHOD AND RESULTS

To systematically study the radiation emitted by the nonlinear crystal, near-field measurements have been conducted by placing a KTP crystal inside a microwave cavity, whose frequency of resonance coincides with the repetition rate of the laser pulses. In this type of detection, the emitted radiation is transferred to the fundamental cavity mode and detected by means of an inductive loop. The loop position in the cavity is initially adjusted to match the condition of critical coupling that allows detection of half the total amount of the generated radiation while the second half is dissipated on the cavity walls. As shown in Figure 1, we used a rectangular cavity C, designed so as to sustain the TE110 mode, whose frequency could be adjusted by means of a moving wall to match the repetition rate of the laser pulses.

The laser polarization orientation dependence of the microwave signal \( V_{RF} \) and of the SHG has been studied with the experimental setup whose scheme is shown in Fig. 1 (bottom). The laser polarization is rotated relative to the crystal axes by means of a \( \lambda/2 \) wave plate mounted on a rotating goniometer. The light exiting the crystal output face contains both the contribution due to SHG and the pump laser, we select the SHG by a combination of a harmonics separator (HS) and a bandpass filter (F). The photodiode (PD) output signal is \( V_G \). The laser stability is monitored during the measurements with a bolometer (B).

![Fig.1. Study of the microwave generation phenomenon inside a rectangular microwave copper cavity. (top) The rotating goniometer G is joint to an internal nonlinear crystal PVC mounting, not visible in the picture. The moving wall structure MW allows the tuning of the cavity proper frequency to the repetition rate of the laser pulses. The critically coupled antenna A allows detection of half of the microwave emitted radiation. (bottom) Block diagram of the experiment. L = laser, T = pulse train, \( \lambda/2 \) = retarding plate, C = cavity, KTP = crystal, A = Antenna, TL = transmission line, S = scope, HS = harmonic separator, F = filter, PD = photodiode, B = bolometer.](image-url)
Fig. 2. Dependence of the microwave signal amplitude $V_{RF}$ on the $\lambda/2$ plate rotation (left vertical axis). Data fitted by the dotted line correspond to measurements of the SH intensity $V_G$ versus rotation angle of the $\lambda/2$ plate.

Fig. 3. Linear dependence of the microwave amplitude $V_{RF}$ (left scale) versus total laser energy $E_t$ and SH intensity $V_G$ (right scale) for a fixed $\theta$. Note that the total laser energy $E_t$ of the laser train of pulses is proportional to the single optical pulse intensity $I$ through the relation:

$$I = \frac{1}{\Delta t \cdot \tau} \frac{1}{A} E_t,$$

where $\tau$ is the laser pulse duration, $\Delta t$ is the train of pulses duration and $A$ is the beam area.

It is possible to show that

$$V_{RF} = B E_t^2 g(\theta) = C I g(\theta),$$

where $I = (1/2)c\varepsilon_0 E_0^2$ is the laser intensity, $c$ is the speed of light and $\varepsilon_0$ is the vacuum permittivity. $B = B(f, \omega)$ and $C = B/c\varepsilon_0$ 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. $g(\theta)$ is a function of the nonvanishing elements of the nonlinear susceptibility tensor [1]. Eq. (3) explains both the results for $V_{RF}$ in Fig. (2) and in Fig. (3). The $V_{RF}$ data in Fig. (3) are measured at fixed angle $\theta$. 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. (2) are obtained at constant $I$, so they display the behavior of $g(\theta)$.

A CONTACTLESS PHOTODETECTOR

The phenomenon of microwave generation by optical rectification of laser pulses can be exploited to develop a new diagnostic tool to characterize trains of high repetition rate laser pulses. We have in fact described a completely passive technique in which high frequencies are available due to the high harmonic content of the optical pulse train. No physical limitations are imposed by the nonlinear crystal itself, and thus very precise frequencies can be specified if the generated radiation is transferred to a microwave receiver whose bandwidth includes $V_{RF}$. Furthermore, no electrical connections are required to obtain a signal proportional to the incident laser intensity, thereby obviating the problems related to parasitic capacitances that arise in the development of ultrafast photodetectors.

Fig. 4. Nonlinear crystal mounting inside the waveguide.

The novel detector key element is a nonlinear optical crystal, enclosed inside a coaxial structure that acts as a receiver of the emitted microwave radiation, as shown in Fig. 4. In contrast to the narrow-bandwidth detection demonstrated in section 3, the coaxial structure allows wide bandwidth detection of the generated radiation. In fact, the coaxial line has no lower frequency cutoff and it supports higher order TE and TM waveguide modes in addition to the TEM mode. Observation of the first four microwave harmonics of the train of pulses (the fourth harmonic corresponds to 18.6 GHz) was possible through propagation of TE and TM modes [2]. Application of the device to the detection of much higher repetition rates in pulsed laser systems could also take advantage of the availability of commercial waveguides up to the D band (90 – 180 GHz).