Generation of tunable pulsed microwave radiation by nonlinear interaction of Nd:YAG laser radiation in GaP crystals

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Pulsed microwave radiation in a tuning range from 10 to 30 GHz has been generated through the parametric interaction of two near-infrared pulses in GaP crystals at low temperatures. The power of the microwave pulses (duration 30 nsec) was of the order of 1 mW. The pump pulses were generated with a Nd:YAG laser emitting simultaneously at two frequencies, within the bandwidth of the 1.064-μm transition, as a result of an étalon output coupler.

The generation of microwave difference frequencies was demonstrated first by mixing axial modes of a ruby laser in crystalline quartz.[1] Microwaves were also generated by mixing adjacent vibrational–rotational lines of a Q-switched CO_2 laser in GaAs crystals[2]; the microwave power at the difference frequency (53.5 GHz) between the $P(18)$ and $P(20)$ CO_2 laser lines was estimated to be several microwatts. Recently[3] the 3-GHz-bandwidth beam of a pulsed dye laser was passed through a Fabry–Perot étalon with a free spectral range adjustable from 2.6 to 4 GHz. Tunable microwave radiation within this frequency range was generated by focusing the étalon output into a $LiTaO_3$ crystal. A microwave peak power in the nanowatt range was obtained. In this Letter a microwave source with a tuning range from 10 to 30 GHz and with a peak power of milliwatts, based on difference frequency mixing, is reported.

The experimental arrangement is shown in Fig. 1. A commercial Q-switched Nd:YAG laser produced pulses of 30-nsec duration with energies up to 200 mJ. As the output coupler an étalon consisting of two 3-mm-thick and slightly wedged quartz plates was used. By moving one of the plates parallel to the resonator axis, the free spectral range ν of the étalon was changed. With this simple arrangement simultaneous lasing at two lines, ν_1 and $\nu_2 = \nu_1 + \nu$, was obtained for values of ν between 10 and 30 GHz; the 1.064-μm line of Nd^{3+} in YAG is homogeneously broadened and has a width of 6.5 cm^{-1}.[4] For spectral measurements of the synchronous laser output the laser radiation was frequency doubled and analyzed with a double-grating monochromator.

The 1.064-μm radiation was guided onto a 4-mm-thick GaP crystal mounted inside an optical cryostat. Laser radiation leaving the crystal was blocked with black polyethylene. For measurement of the wavelength of the microwave radiation a standing-wave resonator was attached to the cryostat. Microwave power was coupled out with a small antenna movable in a slit along the waveguide and was detected with a Schottky diode detector. The diode signal was displayed on an oscilloscope and recorded with a transient recorder.

A microwave pulse is shown in the inset of Fig. 1. The pulse duration corresponds to the duration of the pump pulse and was about 30 nsec. Peak signal voltages of 100 mV were obtained; this corresponds, according to data on Schottky diodes,[5] to a pulse power of milliwatts. A similar power was obtained by an independent calibration with radiation of a klystron. The pump radiation was unfocused (beam diameter $\simeq$ 4 mm) and had a pulse energy of 200 mJ. The signal was obtained by placing the detector near the cryostat output window; the standing-wave resonator was removed. The crystal temperature was 30 K.

The microwave radiation was spectrally analyzed by measuring the microwave intensity inside the standing-wave resonator. Results are shown in Fig. 2 for three different settings of the laser étalon output coupler. Spectra of the corresponding second-harmonic

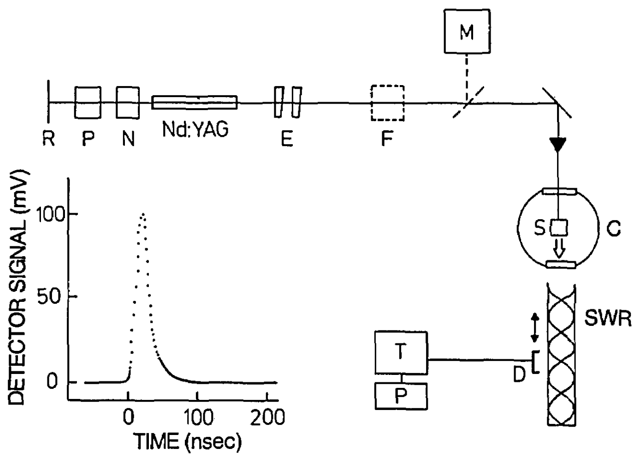

Fig. 1. Experimental setup: R, 100% mirror; P, Pockels cell; N, Nicole prism; E, étalon output coupler; F, frequency doubler; M, monochromator; C, cryostat; S, GaP sample; SWR, standing wave resonator; D, Schottky diode detector; T, transient recorder; P, plotter. The inset shows a detector signal at a pump-pulse energy of 200 mJ.

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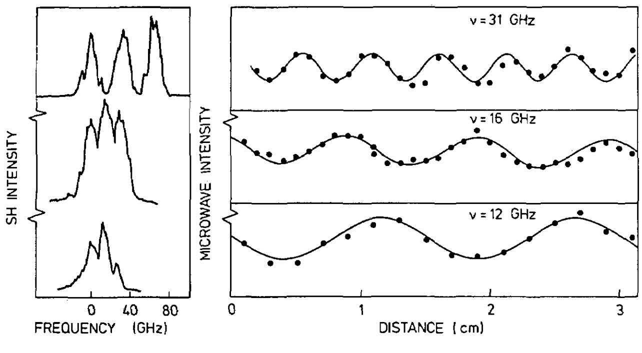

Fig. 2. Spectra of second-harmonic (SH) laser output, left, and microwave intensity along the standing-wave resonator, right, for three different settings of the étalon output coupler.

laser radiation at 532 nm are shown in the left-hand part of the figure. The spectra show three lines, corresponding to $2\nu_1$, $\nu_1 + \nu_2$, and $2\nu_2$. The horizontal scale gives the frequency distance relative to $2\nu_1$, measured with the monochromator. The value of ν for an actual étalon setting corresponds to the frequency separation between two neighboring peaks.

The microwave intensity inside the standing-wave resonator is shown in the right-hand part of Fig. 2. The experimental points are obtained by moving the antenna–Schottky-diode assembly stepwise along the waveguide. The distance l from an arbitrary starting point is given on the horizontal axis. The curves (solid lines) correspond to the expression $\cos^2(2\pi l/\lambda_w)$ for the microwave intensity distribution along the waveguide, where λ_w is the microwave waveguide wavelength. From the experimental values of λ_w (1, 2, and 3 cm) and the waveguide dimensions, microwave frequencies ν (Fig. 2) are obtained that are in good agreement with the optically measured difference frequencies.

The dependence of microwave intensity on crystal orientation is shown in Fig. 3a. The crystal was aligned with the [110] axis parallel to the pump beam (see Fig. 3a) and rotated around this axis. The horizontal scale gives the angle θ between the $[00\bar{1}]$ axis and the polarization E of the pump laser. A maximum is observed at 55° when $[1\bar{1}\bar{1}]$ is parallel to the polarization, followed by a relative minimum at 90° when $[1\bar{1}0]$ is parallel to the laser polarization. This dependence of power on angle is expected for crystals of the class $\bar{4}3m$ to which GaP belongs. It can be easily shown that, for the geometry used, the effective nonlinear coefficient d_{eff} is related to θ by

$$d_{\mathrm{eff}} = d_{14} \sin\theta (4 - 3\sin^2\theta)^{1/2}\,, \tag{1}$$

where d_{14} is the electro-optic nonlinear coefficient. For $\theta = 90°$ ($E \parallel [1\bar{1}0]$), $d_{\mathrm{eff}} = d_{14}$, and for $\theta = 55°$ ($E \parallel [1\bar{1}\bar{1}]$), the maximum value $d_{\mathrm{eff}} = 1.15 d_{14}$ is obtained. The emitted power is proportional to the squared effective nonlinear coefficient, as follows from relation (2). The solid curve in Fig. 3a shows the dependence $(d_{\mathrm{eff}})^2$ on angle θ, normalized to the experimental points at $\theta = 55°$.

The dependence of microwave intensity on pump-pulse energy P is shown in Fig. 3b. P has been varied between 1 and 200 mJ, leading to a change of nearly 4 orders of magnitude in the microwave intensity. The Schottky detector signal is proportional to P^2 (solid line). At high P, a deviation from this behavior is observed that may be attributed to detector saturation.

In the collinear pumping-beam arrangement that was used, the growth of the microwave difference-frequency power can be obtained within a coherence length $L_c = \frac{1}{2}\lambda_m(n_m - n_i)^{-1}$,[6] where $\lambda_m = c/\nu$ is the microwave vacuum wavelength and n_m and n_i are the indices of refraction for the microwave and the YAG laser radiation. With $n_i = 3.1$ and $n_m = 3.35$ (Ref. 7) for GaP, values $L_c \geq 2$ cm are obtained for $\nu \leq 30$ GHz. It should be possible to reach larger values of L_c by using loaded waveguides.[2] Because of the strong absorption ($\alpha \simeq 3\ \mathrm{cm}^{-1}$) of the pump radiation, probably caused by impurities, crystals could be pumped only over a length of about 2 mm, which is much smaller than L_c. Therefore the phase is almost perfectly matched over the interaction length in the crystal, and the microwave power is given by[6]

$$P_m = 8\pi^2 \left(\frac{\mu_0}{\epsilon_0}\right)^{1/2} \frac{P_1 P_2 L^2 {d_{\mathrm{eff}}}^2}{A {\lambda_m}^2 {n_i}^2 n_m}\,, \tag{2}$$

where P_1 and P_2 are the powers of the pump radiation at the frequencies ν_1 and ν_2, L is the interaction length, and A is the area of the cross section of the pump beam. With the values $P_1 = P_2 = 3$ MW corresponding to a total pump-pulse energy of 200 mJ, $A = 0.15\ \mathrm{cm}^2$, $\lambda_m = 2.5$ cm, and $d_{\mathrm{eff}} \simeq d_{14} = 2.3 \times 10^{-11}$ m/V,[8] a microwave power $P_m \simeq 1$ mW is obtained, in agreement with the experiment.

The GaP crystal available for this experiment contained impurities, the most prominent being sulfur of a concentration of 10^{16} to $10^{17}\ \mathrm{cm}^{-3}$, according to the supplier (Siemens). The impurities are ionized at

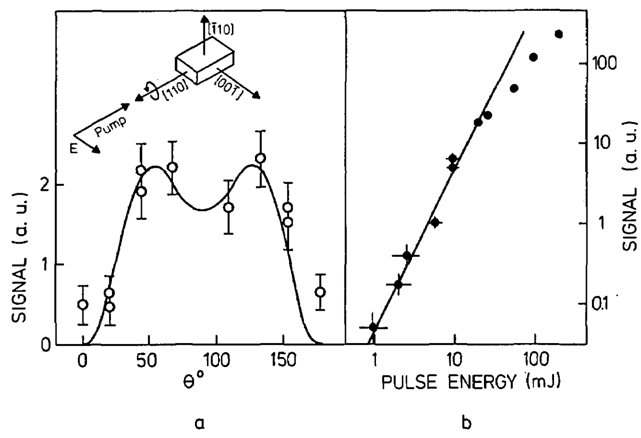

Fig. 3. (a) Microwave intensity versus angle θ between pump-beam polarization E and $[00\bar{1}]$ axis; the [110] axis, parallel to the pump beam, is the rotation axis. The solid line corresponds to ${d_{\mathrm{eff}}}^2$ of Eq. (1). (b) Dependence of microwave intensity on pump-pulse energy. The straight line corresponds to a quadratic behavior.

higher temperatures and cause strong absorption of the microwave radiation. Therefore the experiment was carried out at a crystal temperature of 30 K. The microwave intensity decreased by 50% at 90K, and for $T > 130$ K the intensity was smaller than 1% of the low-temperature value. A similar behavior has been observed in a transmission experiment using a 10-GHz klystron as a microwave source. The dependence of the microwave transmission on temperature can be explained well by assuming absorption due to shallow impurities with ionization energies in the range of 50 to 100 MeV, which is a typical energy range for shallow impurities in GaP.

In conclusion, tunable microwave nanosecond pulses have been generated by difference-frequency mixing of optical pulses from a Nd:YAG laser. A tuning range from 10 to 30 GHz has been demonstrated, and the microwave wavelength has been determined directly from the intensity distribution inside a standing-wave resonator. For the first reported time a microwave power in the milliwatt range has been reached by using an optical nonlinear generation technique. A further increase of microwave power is expected by using crystals that have negligible absorption at the 1.064-μm pump wavelength.

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