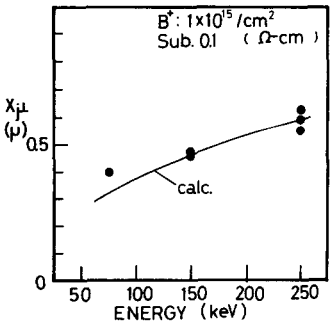

FIG. 3. Implanted energy dependence of the maximum lateral spread of the p-type region ($X_{j\perp}$) fabricated by B^+ ion implantation. The implanted dose was $1\times10^{15}/cm^2$ in all samples.

and Z the directions perpendicular and parallel, respectively, to the mask window of stripe patterns. $\langle\Delta R_p\rangle$, $\langle\Delta Y\rangle$, and $\langle\Delta Z\rangle$ represent the standard deviations of implanted ions in the X, Y, and Z directions, respectively. $2d$ is the width of the mask window, and Q is the number of ions implanted per unit area. The values of $\langle R_p\rangle$, $\langle\Delta R_p\rangle$, and $\langle\Delta Y\rangle$ used in the calculation of $X_{j\perp}$ were 5483, 1227, and 1613 Å, respectively, in the case of implantation with 150-keV B^+ ions, which were calculated by Furukawa *et al.*[2] using the LSS theory.[3]

The dependence of the maximum lateral spread of the p-type region from the mask edge on the implantation dose and on the implantation energy are shown in Figs. 2 and 3, respectively. The solid lines indicate $X_{j\perp}$ calculated from Eq. (1). The value of $X_{j\perp}$ obtained was found to depend scarcely on the annealing temperature in the range 400–800 °C.

The maximum lateral spreads measured in the samples of higher impurity concentration ($6\times10^{16}/cm^3$, 0.1 Ω cm) show relatively good agreement with the calculated ones. The maximum lateral spread of the p-type region in 0.1-Ω cm wafers ranged from 0.4 to 0.6 μ, depending on the various implantation and annealing conditions mentioned above. In the samples of lower impurity concentrations ($2\times10^{15}/cm^3$, 2 Ω cm), the measured values were larger than the calculated ones by 0.1–0.2 μ. Probably this deviation would be caused by the relatively large extension of the depletion layer toward the substrate when the junction is Cu stained. This amounts to about 0.6 μ for 2-Ω cm wafers and 0.13 μ for 0.1-Ω cm wafers, when the maximum photovoltage (0.5 V) is assumed to be introduced in the process of the Cu staining.

The dotted line in Fig. 2 shows junction depths in 0.1-Ω cm wafers obtained by using the values of $\langle R_p\rangle$ and $\langle\Delta R_p\rangle$ calculated by Furukawa *et al.*,[2] which are almost the same as those of Johnson and Gibbons.[4] The smaller open circles are those obtained from present experiments. The discrepancy between the two may arise from the fact that the actual boron ion range is smaller[5] than the calculated one.[2,4] Anyhow, the experimental results indicate that the maximum lateral spread from the mask edge ($X_{j\perp}$) is about half the junction depth X_j (0.85–0.95 μ). On the other hand, as is well known, junctions fabricated by thermal diffusion spread to the lateral direction as well as to the depth direction.

In conclusion, the maximum lateral spread is well represented by Eq. (1), where the lateral spread is expressed as a complementary error function with the standard deviation calculated using the LSS theory.

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Stimulated parametric fluorescence induced by picosecond pump pulses*

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Stimulated parametric fluorescence emission tunable over the range from 0.96 to 1.16 μ has been obtained using a barium sodium niobate crystal pumped by a frequency-doubled and mode-locked Nd^{3+}:glass laser. The pump radiation in the form of a train of picosecond pulses produced infrared parametric fluorescence pulses, less than 10 psec in duration and with average peak powers on the order of 300 W when pumped with a power density of 300 MW/cm^2.

Various techniques have been described for obtaining frequency-tunable ultrashort light pulses, including mode-locked dye lasers,[1] mode-locked parametric oscillators,[2] and stimulated Raman lasers pumped with a mode-locked laser source.[3]

In this letter we report details of observations of frequency-tunable stimulated parametric fluorescence produced by a barium sodium niobate crystal ($Ba_2NaNb_5O_{15}$) pumped with 0.531-μ picosecond light pulses from a frequency-doubled and mode-locked Nd:glass laser. We

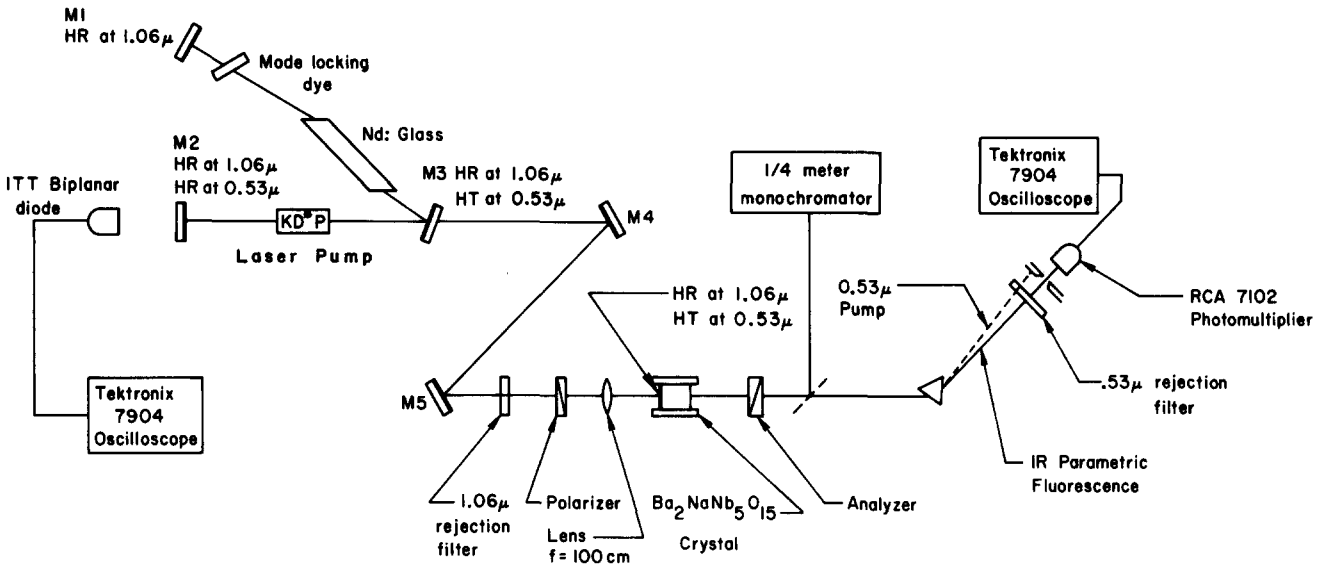


FIG. 1. Experimental arrangement for the generation and detection of optical parametric fluorescence induced by a picosecond pulsed pump source.

describe the first reported measurements of the frequency tuning characteristics with temperature of parametric fluorescence produced under these conditions. In addition the fluorescence output energy as a function of pump power density was measured quantitatively. Individual fluorescence pulses were resolved temporally for the first time using a fast real-time detection system. The most important experimental factor contributing to successful detection of the parametric fluorescence signal was the provision of a high degree of isolation of the infrared pump from the comparatively low-power parametric fluorescence signal.

Although the possibility of parametric formation of ultrashort fluorescence induced by picosecond optical pulses was discussed previously by two groups,[4,5] very few quantitative results were published by either of these groups. In addition, Yarborough and Massey[6] reported on high-gain parametric generation in an ADP crystal continuously tunable across the visible spectrum pumped with relatively long pump pulses (~3 nsec) from a frequency-quadrupled Nd:YAG laser.

The experimental apparatus used in the present work is shown schematically in Fig. 1. The frequency-doubled Nd:glass laser pump has been described previously.[7] The 0.531-μ pump radiation available from this source consists of pulse trains of about 50 pulses of 4-psec duration with peak powers of about 100 MW. The mirrors M4 and M5 serve to steer the pump beam and simultaneously discriminate against the 1.062-μ background radiation leaking from the mode-locked pump laser by being highly reflective at 0.53 μ and highly transmissive at 1.06 μ. A long-focal-length lens (f = 100 cm) is used to lightly focus the green picosecond pulses into a 5-mm-long $Ba_2NaNb_5O_{15}$ crystal. The crystal is oriented with its optic axis at 90° to the pump propagation direction and is located in an oven whose temperature can be accurately set to the desired phase-matching temperature. The effective pump power density could be as high as 300 MW/cm^2 without damaging the nonlinear crystal. By careful adjusting of the mode-locking dye concentration and pump energy of the Nd:glass laser flashtube, it was possible to double the effective pump power. At these power levels the crystal exhibited surface damage after one or two measurements. The crystal was coated on the front surface for additional discrimination against any 1.06-μ background radiation. Further discrimination in studying the infrared fluorescence output collinear with the 0.531-μ

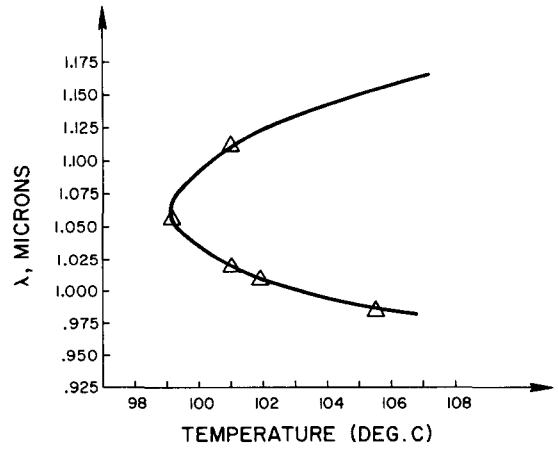
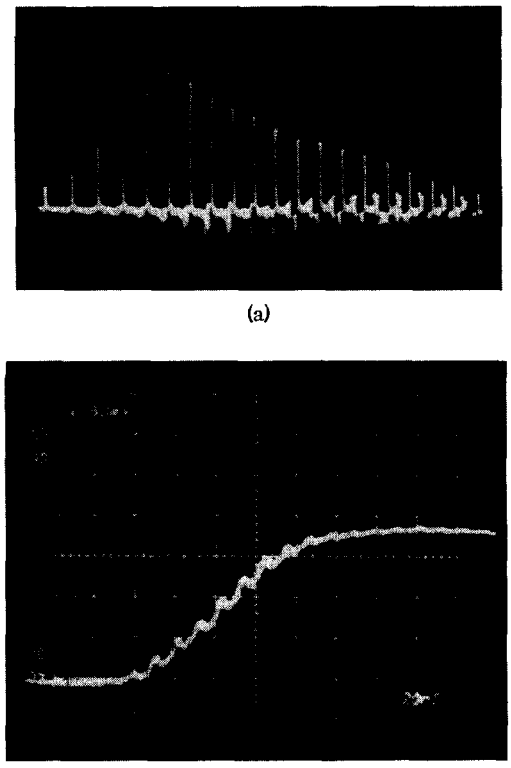


FIG. 2. Temperature tuning curve of the parametric fluorescence generator. The solid line represents data taken with a frequency-doubled Q-switched Nd:YAG laser while the data points (Δ) were obtained with a frequency-doubled and mode-locked Nd:glass laser.



(a)

(b)

FIG. 3. Oscilloscope traces showing (a) a typical pump pulse train observed with a fast photodiode and (b) the parametric fluorescence output obtained with an S1 photomultiplier. Time scale is 20 nsec per major division.

pump was provided by a polarizer, a 0.53-μ rejection filter, and spatial translation by a prism. A 0.25-m monochromator was used to measure the wavelength of the parametrically generated output light. A temperature tuning curve was obtained from 0.96 to 1.16 μ (Fig. 2). When the crystal was rotated 90° or dropped below 99 °C in temperature, fluorescence was no longer observed. The temporal characteristics of a typical pump and fluorescence signal as monitored by a model 7904 Tektronix oscilloscope using an ITT F4000 photodiode and an RCA 7102 photomultiplier, respectively, are shown in Fig. 3. The rise time of the former system is less than a nanosecond, while that of the latter is several nanoseconds. The fluorescence power was determined by measuring the total energy output with an S1 photomultiplier and estimating the number and duration of the fluorescence pulses. Unfortunately, the second-order intensity correlation techniques used for measuring the ultrashort pulse duration of the pump are not applicable to observe the duration of individual fluorescence pulses, since these methods require relatively large powers. The fluorescence power was estimated to be about 300 W for a pump power density of 300 MW/cm^2, assuming the fluorescence pulses to have a duration of 10 psec and a total of 50 pulses per train. This corresponds to an over-all average power conversion efficiency of at least 10^{-4} from the green pump to the infrared fluorescence output. A duration of 10 psec is not unreasonable if we take into account the influence of linear dispersion and consider that, near degeneracy, a 5-mm-long $Ba_2NaNb_5O_{15}$ crystal has a

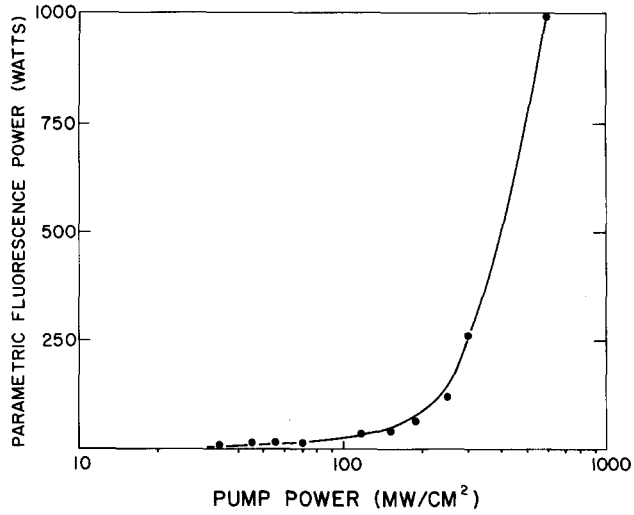


FIG. 4. Plot of the average fluorescence power per pulse as a function of pump power density per pulse.

phase-matchable bandwidth of at least 5 Å.[8] Measurements of the total output energy were made as a function of the input power density. A curve of the fluorescence power as a function of pump power density is shown in Fig. 4. The nonlinear dependence of parametric gain is clearly noticeable. The shape of the curve is in qualitative agreement with the parametric power gain expression derived by Harris[9] for steady-state conditions and by Glenn[10] for transient-state conditions.

The peak fluorescence power is limited by the surface and bulk damage thresholds of the nonlinear crystal for the pump radiation and by the fact that the system is nonresonant and has no feedback as in the usual parametric oscillator. To make the system into an oscillator would be quite difficult because of the pulsed nature of the pump. A cw pump (Nd: YAG, for instance) would make the implementation of a mode-locked optical parametric oscillator much easier.

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