Generation of 22 mW of 532-nm radiation by frequency doubling in Ti:MgO:LiNbO₃ waveguides

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We report temperature phase-matched second-harmonic generation of 1.064-μm radiation in Ti-indiffused waveguides in MgO-doped LiNbO₃ substrates. Noncritical phase matching of the TE_2 mode was achieved at 102–106°C. Owing to the high-temperature operation and the low photorefractivity of the waveguide, it was possible to generate 22-mW average-power 532-nm output. No evidence of photorefractive scattering was observed during 5 h of operation at 3-mW output.

The efficiency of nonlinear-optical interactions in planar dielectric waveguides is enhanced by a combination of long interaction length and tight beam confinement impossible in bulk crystals.[1] Lithium niobate is frequently used as a substrate for guided-wave nonlinear interactions because it has large nonlinear susceptibilities and is sufficiently birefringent to phase match a variety of interactions in the visible and near infrared. Conversion efficiencies for second-harmonic generation (SHG) of 532-nm radiation as large as 1.5 × 10^{-2}% cw[2] and 25% pulsed[3] have been reported. The maximum average power observed at 532 nm has been 112 μW.[3]

These results and most other interactions involving visible light in LiNbO₃ waveguides have been limited by photorefractive damage effects.[3,4] Recently Zhong et al. reported that LiNbO₃ doped with MgO (MgO:LiNbO₃) shows substantially reduced photorefractivity,[5] which Brown et al. have attributed to increased photoconductivity.[6] The potential for high-power nonlinear devices in the visible region motivated this study of frequency doubling in Ti:MgO:LiNbO₃ waveguides.

The planar waveguides were fabricated by a standard Ti-indiffusion process in x-cut MgO:LiNbO₃ substrates from a boule grown out of 5% MgO-doped melt by Crystal Technology, Inc. A 30-nm layer of Ti was deposited upon the substrates, followed by diffusion in a wet oxygen atmosphere with a 4°C/h ramp to the soaking temperature, a soak interval, and an 8°C/h ramp to room temperature. Soak temperatures between 1030 and 1070°C and 10–20-h soak intervals were used. An inverse WKB analysis of the measured effective mode indices yielded waveguide depths that generally agreed to within 20% with calculations using literature values for the diffusion coefficient.[7] Unless otherwise noted, the harmonic-generation results reported here are for a Gaussian-profile waveguide with a 1/e depth of 2.2 μm and Δn_e and Δn_o of 0.011 and 0.005, respectively, at 532 nm. One TM mode at 1.064 μm and three TE modes at 532 nm were observed.

For the SHG experiments, the output of a Nd:YAG laser was focused approximately confocally with a cylindrical lens and coupled into the TM_0 mode of the waveguide with a rutile prism. After a 13-mm interaction length along the y axis, the 532-nm output and the unconverted 1.064-μm radiation were outcoupled with another rutile prism.

The phase-matching temperature (T_{pm}) in bulk MgO:LiNbO₃ is 107°C.[6] Peaks in the conversion efficiency were observed in the waveguide at 21.7 and 102.0°C, corresponding to conversion into the TE_0 and TE_2 modes, respectively. The normalized second-harmonic (SH) output power versus temperature for the TE_2 mode is shown in Fig. 1. The temperature bandwidth of 1.15°C-cm is larger than the 1.0°C-cm that we measured in the bulk, indicating slight optical or thermal inhomogeneity in the waveguide. Other waveguide samples showed a T_{pm} of 102–106°C for the TE_2 mode.

The lower T_{pm} observed for the guided modes is expected from the decrease in birefringence that is due to the Ti indiffusion. The reduction below the bulk value of the phase-matching temperature can be related to the change in birefringence ΔB between the TM_0 (1.064-μm) and the TE_n (532-nm) modes, where

$$\Delta B(TE_n) = [n_{eff}(TE_n) - n_e(bulk)]_{532\,nm} - [n_{eff}(TM_0) - n_0(bulk)]_{1.064\,\mu m}.$$

These changes were calculated from mode-index measurements as $\Delta B(TE_0) = 0.0054$, $\Delta B(TE_1) = 0.0011$, and $\Delta B(TE_2) = 0.0003$. The temperature coefficient of the birefringence, measured from the spacing of the efficiency peaks in the temperature phase-matching curve (Fig. 1), is $d[n_e(532\,nm) - n_0(1.064\,\mu m)]/dT = -6.8 \times 10^{-5}$/°C. The phase-matching temperatures predicted from these data are $T_{pm}(TE_0) = 27.6$°C, $T_{pm}(TE_1) = 90.8$°C, and $T_{pm}(TE_2) = 102.6$°C. These calculated values agree well with the experimental data for the TE_0 and TE_2 modes. The low conversion efficiency of the TE_1 mode prevented measurement of its phase-matching temperature, as is discussed in greater detail below.

The output face of the waveguide was polished to permit direct output coupling and facilitate power
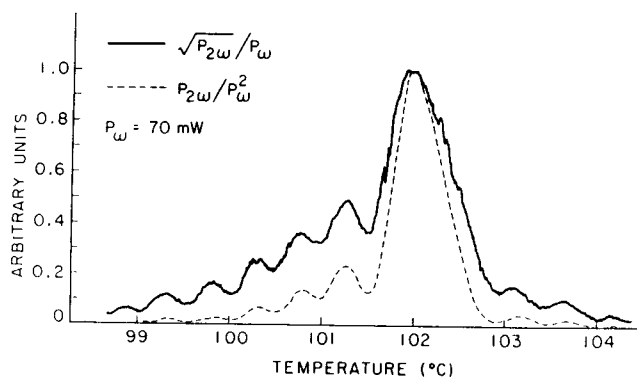
HARMONIC CONVERSION EFFICIENCY vs TEMPERATURE

Fig. 1. Normalized TE_2 SH output power versus temperature. The dashed curve was obtained by squaring the raw data plotted as a solid line.

measurement for the determination of absolute conversion efficiency. In this case the interaction length was 19 mm. Prism launching efficiency so measured was typically 30–50%. Prism outcoupling was used only for relative power measurements, e.g., temperature phase-matching curves. All values for absolute powers reported in this Letter are direct outcoupled powers corrected for the 14% endface reflection loss. The square root of the SH power is plotted versus the fundamental power in Fig. 2. The specific conversion efficiency, defined as $P_\omega/(P_{2\omega})^2$, calculated from the slope of the line, is 0.6%/W. The specific conversion efficiency varied between 0.5 and 0.6 %/W for cw 532-nm outputs up to 0.87 mW. The maximum 532-nm output was limited only by the available input power at 1.064 μm. The conversion efficiency for the TE_0 mode was 8×10^{-5} %/W.

Theoretical prediction of the conversion efficiency involves calculation of the overlap between the SH and fundamental modes. However, it is difficult to calculate the modal field accurately for the nearly cutoff TM_0 mode of this waveguide at 1.064 μm. Qualitatively, the overlap of the loosely guided TM_0 mode with the tightly guided TE_0 mode is expected to be small compared with that with the less tightly guided TE_2 mode. This situation would explain the considerably lower efficiency observed for the TE_0 mode. It is suspected that the TE_1 mode overlap was smaller than that of the TE_0 mode because of the additional phase reversal involved. Our inability to observe the TE_1 mode was probably due to its small output's being masked by the low-temperature tail of the TE_2 mode generation.

The specific conversion efficiency could be improved considerably if the fundamental mode were more tightly confined by increasing the refractive-index difference or the depth of the waveguide. One 4.8-μm-deep waveguide did show several times the conversion efficiency reported here, but detailed measurements were impossible because of the oxygen-loss problem discussed below.

Characterization of the photorefractive effect in a $LiNbO_3$ waveguide is complicated by the detailed de-

pendence of the damage on the thermochemical and optical history of the device and by the characteristic equilibration times that can reach hundreds of hours.[4] In addition, the photorefractive effect can manifest itself in a variety of ways whose relative importance depends on the application. Sensitive techniques have been developed for the measurement of small photorefractively induced changes in the index of refraction important to interferometric devices.[8] For nonlinear optics, the important phenomenon is photorefractively induced blooming of the interacting beams. While there is no single quantity suitable for the characterization of these varied effects, the time dependence of the SH power transmitted through a slit is a reasonable measure of the photorefractive sensitivity of a waveguide for nonlinear-optical applications.

To characterize the short-term photorefractive sensitivity, the 532-nm beam generated by the SHG process was passed through a slit perpendicular to the plane of the waveguide. After the slit was centered on the beam, its width was adjusted to obstruct half of the output at low power. The 1.064-μm pump power was then raised to bring the 532-nm output to the desired level. The slit throughput was measured with a photodiode and recorded on a strip-chart recorder. The particular choice of one half as the fraction of output power blocked by the slit is arbitrary, but a significantly wider slit reduces sensitivity to photorefractively induced blooming of the beam, while a significantly narrower slit unnecessarily reduces the throughput. Plots of the throughput versus time are shown in Fig. 3 for several power levels. At the maximum cw power of 800 μW the throughput of the best waveguide did not decay measurably over the measurement period of 1 h. Changes in the waveguide characteristics, later understood to be related to oxygen loss, prevented quantitative measurements of the decay for pulsed outputs, but average powers of 4 mW did not decay over at least tens of minutes, while at 22 mW the throughput decreased significantly in several minutes.

The optical properties of the waveguides changed in an unpredictable fashion after exposure to elevated temperatures. It was observed that the conversion efficiency, phase-matching temperature, and damage susceptibility of the best waveguide were reproducible for different input powers and at different locations in
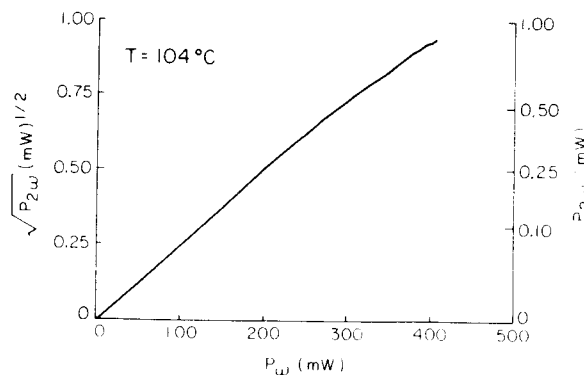

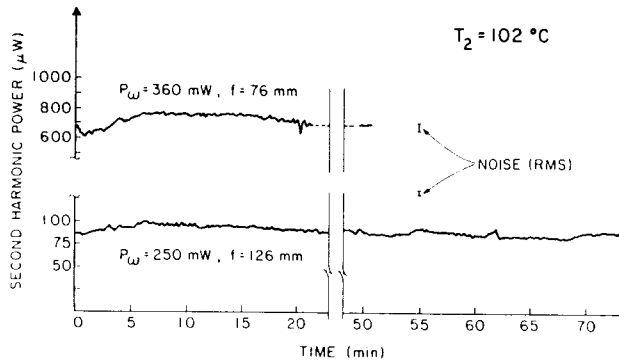Fig. 2. Square root of the TE_2 SH power plotted versus input power.

Fig. 3.   TE$_2$ SH output through a slit plotted versus time. Lens focal length and fundamental power are indicated on the plot.

the waveguide over tens of hours at 100–110°C. However, after the waveguide was heated to 280°C for 4 h in ambient atmosphere to remove photorefractive damage caused by 22-mW 532-nm beams, the phase-matching temperature dropped to ≈98°C. The damage susceptibility increased dramatically, visible beam blooming occurring after several minutes of operation at less than 5 μW, compared with 1 h of operation at 800 μW without measurable damage before the heat treatment. Two other waveguides showed the same problems after 1–2 h at temperatures that did not exceed 110°C. Neither the reason for the differences between the waveguides nor the mechanism causing the increased damage susceptibility is known. The increased damage susceptibility appears to be related to the well-known tendency of LiNbO$_3$ to lose oxygen at relatively low temperatures. The phase-matching temperature of our samples was increased and their damage susceptibility reduced by annealing in pure dry oxygen at 125°C for 6 h. The phase-matching temperature of the best waveguide increased from 98 to 106°C after annealing. Further study will be necessary to quantify and understand these effects, but it appears that control of the atmosphere during processing and some means of preventing oxygen loss during use may be necessary for successful operation of Ti:MgO:LiNbO$_3$ waveguides at elevated temperatures.

The photorefractive sensitivity measurements were repeated for pulsed inputs, while the waveguide was maintained under a pure dry oxygen atmosphere. After 5 h at a 3-mW average output level, the fraction of the output passing through the slit was unchanged, a significant improvement over the damage at 5-μW levels observed before the oxygen treatment. Experimental difficulties prevented measurements at higher output powers, so it was not possible to determine the damage threshold under an oxygen atmosphere.

Preliminary comparisons of Ti:MgO:LiNbO$_3$ and Ti:LiNbO$_3$ waveguides at room temperature indicate that the improvement in the power-handling capacity of the MgO-doped material is substantially degraded by Ti ions. Thus the high damage thresholds that we observed are probably due in large part to the higher phase-matching temperature and to a lesser degree to

the intrinsically lower damage susceptibility of the MgO-doped waveguides. As the photorefractive sensitivity appears to be related to the presence of Ti ions, and the loosely guided TE$_2$ mode propagates largely in regions with low Ti concentration, one expects that the susceptibility to damage of well-confined modes will be higher than that observed here. Preliminary results indicate that room-temperature damage is more serious than high temperature and that low-order modes are more susceptible to damage than high-order modes, which supports these suppositions. More-detailed studies of the room-temperature behavior of more strongly guiding Ti:MgO:LiNbO$_3$ waveguides will be reported elsewhere.[9]

We have generated 22-mW average power at 532 nm by SHG of 1.064-μm radiation in a Ti:MgO:LiNbO$_3$ waveguide. It was possible to maintain 3-mW average output power for 5 h without measurable photorefractive damage. The increased damage resistance of the waveguide compared with Ti:LiNbO$_3$ appeared to be due primarily to the higher phase-matching temperature of MgO-doped material and to a lesser extent to intrinsically smaller photorefractive sensitivity. Some of the waveguides deteriorated at 100°C unless maintained in an oxygen-rich atmosphere. While the data obtained to date are not sufficiently detailed to serve as a basis for firm conclusions regarding the role of oxygen in photorefractive effects in Ti:MgO: LiNbO$_3$ waveguides, it is clear that oxygen effects should be kept in mind in interpreting future photorefractivity data. Further study is necessary to understand the oxygen effects and to find processing conditions that lead to improved damage resistance and higher conversion efficiency.

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