Dye laser pumped by Nd:YAG laser pulses frequency doubled in a glass optical fiber

U. Österberg

Institute of Optical Research, Royal Institute of Technology, Stockholm S10044 Sweden

W. Margulis

Department of Applied Physics, Royal Institute of Technology, Stockholm S10044 Sweden

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Efficient frequency doubling of a cw Q-switched and mode-locked Nd:YAG laser has been observed in commercial single-mode optical glass fibers. Pulses of duration ~55 psec and intensities as high as ~0.55 kW were produced at 0.53 μm. The maximum peak power-conversion efficiency measured was ~3%. The frequency-doubled light generated in the glass fibers was sufficient to pump a commercial Rh6G dye laser with ~19% efficiency at 570 nm.

During the past 15 years, nonlinear interactions in glass optical fibers have been extensively studied. Because of the center of symmetry that a Ge-doped silica fiber is supposed to have, all the second-order dipole nonlinear coefficients should be zero, and consistently most nonlinearities reported to date are of third order.[1] Nevertheless, weak sum-frequency generation and second-harmonic generation have also been reported to occur in optical fibers.[2–4] The exploitation of such effects in fibers is of great interest because of the low attenuation, long interaction lengths, low price, and ready availability of such media. For these reasons, efforts have recently been made to grow crystal fibers[5] that could replace the much more expensive nonlinear crystals currently used, such as KTP. In this Letter we report high-efficiency second-harmonic generation (SHG) in a conventional glass fiber and its use to pump a commercial dye laser.

A cw mode-locked and Q-switched Quantronix 114 Nd:YAG laser was employed in the experiments, producing 100–130-psec-long pulses and peak powers as high as 70 kW. Q-switched trains, typically lasting for 450 nsec (FWHM), were generated at a 1250-Hz rate. Two different types of glass fiber were used, one of which is commercially available. Both were prepared by the modified chemical-vapor deposition technique and had 9-μm core diameter and 50- and 125-μm inner and outer cladding diameters, respectively. The core of both types of fiber was Ge doped, and Δn was 0.0035 and 0.0045, and the cutoff wavelength λ_c was 1.20 and 0.95 μm, respectively. Pieces with lengths ranging from less than 1 to 110 m were employed. The light was focused into the fibers with a 13× microscope objective, and typically 30–50% of the light was coupled into the core. In order to remove undesired cladding modes, the plastic protection around the fibers was burned and the exposed outer cladding immersed in glycerin. In all experiments carried out, the IR pump propagated in the fundamental transversal mode (LP01).

At first, no green light was produced, even when the total average power coupled into the core of the fibers was as high as ~300 mW. Visible light in the red spectral region (630–740 nm) was observed, owing to a four-photon process.[6] After a period of steady illumination, weak second-harmonic radiation could also be observed at the output end of the fiber (<3-nW average power). After this initial slow preparation stage, the green intensity grew quickly, as illustrated in Fig. 1. The growth of the SHG efficiency is found to be exponential, to a good approximation, over more than 4 orders of magnitude (linear on a linear–log plot).

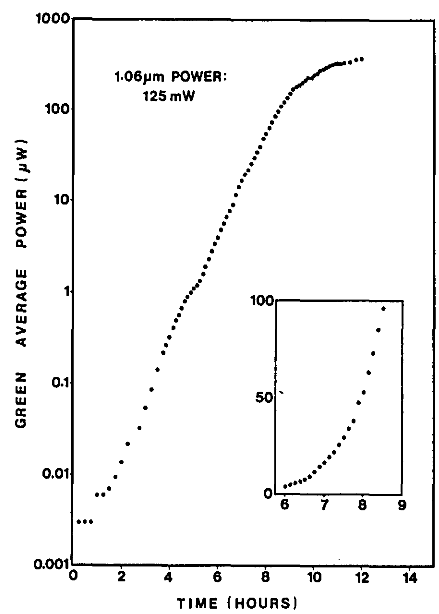

Fig. 1. Output power of second-harmonic light generated in a glass fiber as a function of time. The deviation from a straight line after ~5 h is due to instability in the input IR power. The inset shows the growth rate on a linear scale (same units).

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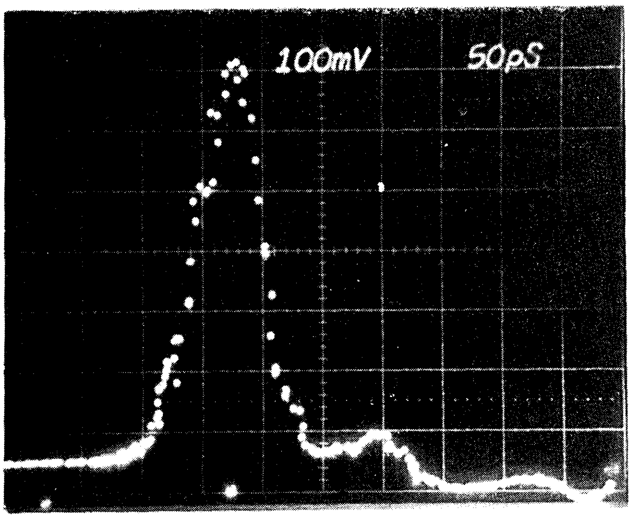


Fig. 2. Oscilloscope trace of individual green pulses on a 50-psec/division time scale.

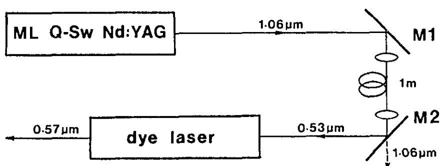
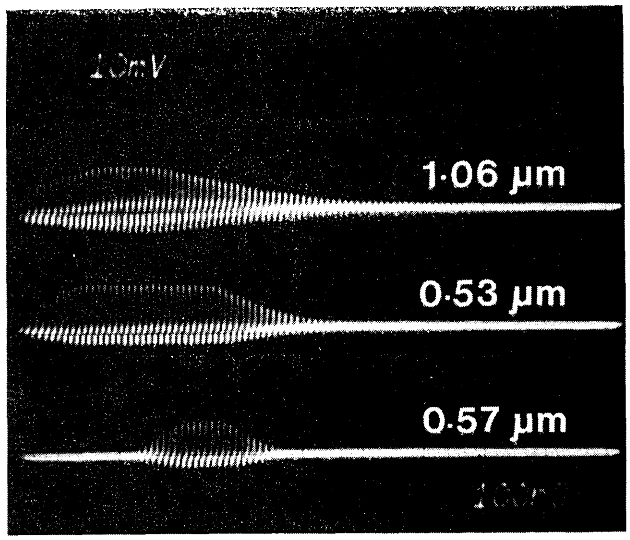


Fig. 3. Experimental setup to pump the dye laser. ML, mode locked.

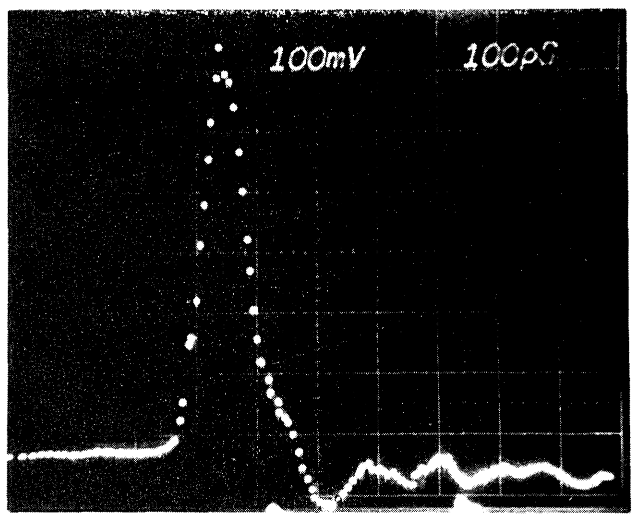
The inset of the figure shows the growth on a linear scale. It was found that the rate of growth depends to a large extent on the IR optical power. After approximately 12 h of Nd:YAG-light illumination the green output power saturated and stopped growing, as can be seen from Fig. 1. This procedure has been repeated for a large number of different fiber lengths, and both types of fiber tested systematically showed the same behavior. Typically, the average power of green light measured was ~0.7 mW, but average powers as high as 1.6 mW were produced, corresponding to a peak pulse power of ~0.55 kW. Since the SHG takes place mainly in the first few centimeters of fiber,[7] and the losses at 0.53 μm are significant (~16 dB/km in one case), the green-intensity output increases markedly when relatively short fiber lengths are used. By varying the intensity of the infrared light coupled into fully prepared fibers and monitoring the IR and green intensities at the output, it was found for 1-m pieces of fiber that the 0.53-μm light's average power depended on the fourth power of the IR input, saturating for very high input powers.[7]

Time-resolved measurements of the green light with picosecond resolution were carried out using an intrinsic Si photoconductor in conjunction with a picosecond electric pulse shaper and a sampling oscilloscope.[8] Figure 2 is an oscillogram of the green-light pulse on a 50-psec/division time scale, and the pulse width (~55 psec), which is close to the oscilloscope's resolution limit, does not exceed half of the pump-pulse duration. This is consistent with the fact that the green light is generated through a nonlinear process of higher order, since a second-order process would give rise to pulses only $\sqrt{2}$ shorter than the IR pulses. Further investigations on the origin of the green light are in progress and will be reported elsewhere.

In order to demonstrate further the high efficiency of the SHG in the glass fibers subjected to the preparation process described above, the green light was used to pump a Quantronix 450 Rh6G dye laser, as schematically shown in Fig. 3. The dye laser had unoptimized mirrors (~15% output coupler) and was aligned and operated in the same way as when optically pumped by the 0.53-μm light from a KTP crystal, resulting in an average pump-power threshold of ~300 μW. The output end of the fiber was placed ~10 cm from the entrance aperture of the dye laser, and the



(a)



(b)

Fig. 4. (a) Trains of pulses from the Nd:YAG laser (top), second-harmonic light from glass fiber (middle), and dye laser (bottom trace) displayed on 100-nsec/division time scale. (b) Oscilloscope trace of individual dye-laser pulse on a 100-psec/division time scale. Pulses as short as ~50 psec were observed.

green light was focused on the dye jet by a 10× microscope objective. Both types of fiber were successfully employed, with lengths ranging from 80 cm to 5 m, chosen for convenience. The maximum average power measured from the dye laser in this unoptimized configuration was 0.21 mW at 570 nm. The maximum pumping efficiency achieved was ~19% for a pump power of 0.96 mW, when the dye-laser output was 0.18 mW. The maximum peak power of the dye-laser pulses generated exceeded 100 W.

Figure 4(a) is an oscilloscope trace of the Q-switched IR pulse train (top), the frequency-doubled signal out from the fiber (middle), and the dye-laser pulse train (bottom trace). From the oscillogram it is apparent that the green light saturates and that the envelope profile is relatively flat, so that the pulses have approximately constant optical power along the train. This flat profile is also impressed on the dye-laser pulse train. From the oscillogram it can also be seen that for this cavity configuration and pumping power, the dye laser reaches threshold only ~150 nsec after the beginning of the optical pumping. An individual dye-laser pulse is shown in Fig. 4(b) on a 100-psec/division time scale. The dye-laser pulse shape and duration were found to follow closely those of the green pulses, and pulses as short as ~50 psec FWHM were measured in the middle of the train. No serious attempts have yet been made to optimize pulse lengths or to compress the pulses produced. Launching large optical powers of IR light into the fiber, thereby ensuring that the green light was in a saturated regime, prevented the possibility that small fluctuations of the Nd:YAG laser could affect the stability of the green; this made possible the generation of stable dye pulses over periods of several hours.

In conclusion, we have described efficient SHG from conventional glass optical fibers that produce sufficient power to pump a commercial dye laser. Although the frequency-doubling efficiency of the fibers is inferior by more than 1 order of magnitude to that of high-quality SHG crystals, the cost is approximately 4 orders of magnitude lower. Further understanding of the physical mechanisms involved in frequency doubling in glass fibers is still required in order to permit optimizing of various parameters. The use of glass fibers for SHG is, however, even at this stage, promising.

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