Efficient Second Harmonic Generation of Picosecond Laser Pulses*

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Efficient conversion to the second harmonic (SH) using KD_2PO_4 and CsH_2AsO_4 crystals inside a folded cavity of a high-power-dye mode-locked Nd^{3+}:glass laser is reported. For the first time, frequency-doubled picosecond light pulses have been obtained in CsH_2AsO_4 with peak powers of the order of 10^9 W/cm^2 at 0.531 μ for an effective pump power density of 4×10^9 W/cm^2.

For a number of applications it is desirable to frequency double the output from high-power mode-locked ruby and neodymium lasers. Second harmonic generation (SHG) in $LiNbO_3$ and KH_2PO_4 (KDP) crystals from picosecond light pulses emitted by a Nd^{3+}:glass laser has previously been studied theoretically and experimentally.[1-3] This letter describes details of an efficient intracavity second harmonic (SH) generator that is capable of producing intense visible coherent radiation in the form of picosecond light pulses. The pump source is a 1.062-μ Nd^{3+}:glass laser which is mode locked and Q switched by means of Eastman Kodak dye 9740 or 9860. The most effective nonlinear optical crystal presently commercially available for generating high-peak-power SHG light pulses was found to be a 90° phase-matchable tetragonal arsenate crystal which belongs to the familiar KDP group.[4] Details of the performance characteristics of CsH_2AsO_4 (CDA) are discussed since they are significantly better than those reported for such other potential SHG materials as KH_2PO_4, KD_2PO_4 (KD*P), $LiNbO_3$, $Ba_2NaNb_5O_{15}$, or $LiIO_3$.

The laser cavity configuration which was found to produce picosecond light pulses at 0.531 μ with the best conversion efficiency is shown in Fig. 1. It is similar to one used by Chesler et al.[5] for a Nd^{3+}:YAG harmonic source. The laser cavity consists of two arms, one containing the Nd:glass rod and mode-locking dye cell and the other arm containing the SHG crystal. The folded cavity approach results in almost complete collection of the harmonic radiation in a single output beam instead of it being absorbed by the laser rod as in a collinear intracavity configuration.

Although numerous nonlinear optical crystals suitable for SHG have been reported in the literature,[6] it is found that the KDP group crystals despite their lower SHG figure of merit[7] are the most efficient in the harmonic production of picosecond pulses. This is true because of the high threshold power density for damage, minimum self-heating effects, maximum angular acceptance of the pump beam due to noncritical phase matchability, and the absence of harmonic pulse broadening due to favorable dispersion characteristics for optimum phase matching of a large linewidth pump. Such new nonlinear optical crystals as $Ba_2NaNb_5O_{15}$ and $LiNbO_3$ possess a large nonlinear coefficient compared to KDP and are 90° phase matchable (undesirable birefringence effects are absent). However, they have damage threshold power levels of only several MW/cm^2 and 100 MW/cm^2, respectively. In addition, these crystals have a narrow acceptance angle for the fundamental radiation and considerable pulse lengthening characteristics.[1-3] Therefore, in this work a new material, cesium dihydrogen arsenate, is employed which is not only 90° phase matchable (at about 45 °C for a 1.062-μ pump), but also possesses a damage threshold of power densities in excess of 500 MW/cm^2. For direct comparison a deuterated potassium dihydrogen phosphate crystal is used, which has the same optical damage characteristics as CDA but is not 90° phase matchable. The SHG output was studied in terms of its temporal characteristics and energy content. Figure 2(a) shows a typical SHG pulse train obtained at the optimum phase-matching angle of 37°5′ at room temperature for KD_2PO_4.[8] The SHG pulse train is similar in shape to the pump pulse train. Pulse widths were measured by means of the two-photon-fluorescence (TPF) technique.[9,10] TPF pho-
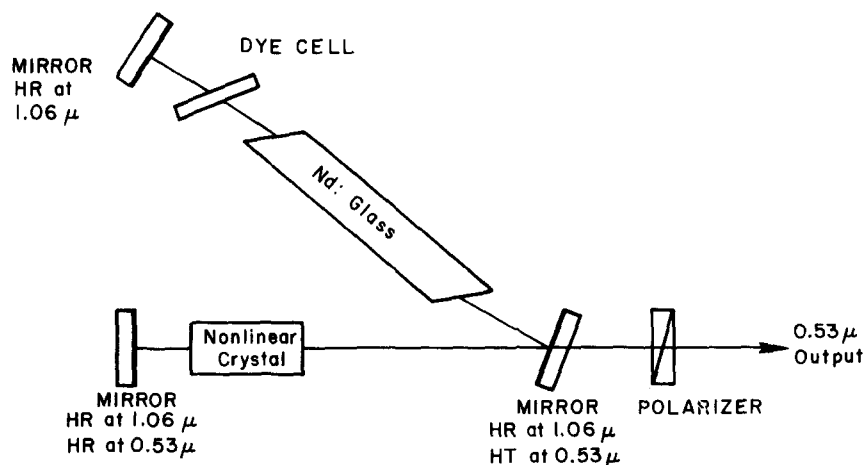

FIG. 1. Schematic diagram of the laser system.
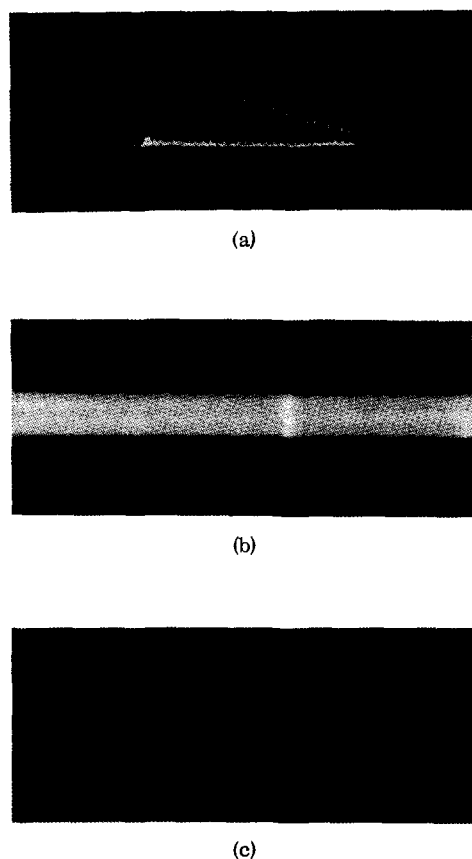
(a)

(b)

(c)

FIG. 2. Temporal characteristics of a SHG picosecond light-pulse train; (a) typical SHG output vs time. The pulses were detected by means of an ITT F4000(S1) and displayed on a Tektronix Model 519 oscilloscope at a sweep speed of 50 nsec/cm; (b) TPF photograph produced by a pump pulse train showing 7-psec pulses; (c) TPF track produced by a SHG KD*P pulse train showing 3-psec pulses.

tographs obtained with both ultrashort pump and harmonic pulse trains are depicted in Figs. 2(b) and 2(c), respectively. The duration of the 1.062-μ pump pulses is of the order of 7 psec, while the duration of the 0.531-μ pulses is only about 3 psec. However, when using a CDA crystal the duration of the frequency-doubled pulses is comparable to the pump pulse lengths which is indicative of a smaller effective spectral phase-matching bandwidth[11] for CDA than KD*P. Calorimetric measurements of the SHG output from a 1.3 ×1.2×3.8-cm KD*P crystal indicated a total energy output of 7.5×10^{-2} J for a 20-cm-long by 0.9-cm-wide laser rod mode locked with a 0.17-cm dye cell containing equal amounts of solvent and dye. The beam cross section external to the cavity is 0.4 cm^2. This corresponds to 1.5×10^{-3} J of energy in a single picosecond pulse or a power density of 10^9 W/cm^2 assuming an average of 50 pulses per train and no satellite pulses. In actual fact, this assumption is not always correct, since photographs obtained with a fast-image-converter camera in a streaking mode of an object illuminated with a 0.531-μ pulse train indicate that what appears to be a single pulse in Fig. 2(c) often belongs to a group of 3 to 4 pulses. Since these "satellite" pulses were separated by an interval of about 300 psec, they are not

recorded in the TPF measurements. The equivalent total energy output of the laser system at 1.062 μ is of the order 0.3 J, so that the SHG conversion efficiency is 25%. For a much shorter CDA crystal (1.3×1.3 ×1.3 cm) the 0.531-μ energy output is 5×10^{-2} J. The measured output-beam cross-sectional area is only 0.1 cm^2 apparently caused by internal focusing of the pump due to the accidental curvature of the CDA crystal. In this case, the output power density is 10^9 W/cm^2 although CDA has a figure of merit of only one-fourth that of KD*P.[5] Furthermore, the near- and far-field intensity distribution of the SH beam appears to be more uniform than when using KD*P. According to the SH theory by Boyd and Kleinman,[12] an even larger SHG output and efficiency should result if higher intracavity pump power levels are available at power densities below the optical damage threshold of any of the optical components and if CsD$_2$AsO$_4$ (CD*A) is used, since the absorption loss for CD*A is of the order of 1%/cm as compared to about 4%/cm for CDA.[13] The angular acceptance range is measured to be about 2.5° for CDA permitting optimum utilization of a multitransverse-mode Nd:glass pump beam. No specific attempt was made to minimize the angular divergence of the pump beam which is 2×10^{-3} rad. Figure 3 shows the SHG characteristics of temperature and orientation phase-matched CDA and orientation phase-matched KD*P crystals. The significant difference in half-power width for the two materials is clearly evident. From this a further advantage of the arsenates is apparent in that the requirements for phase-matching temperature control and oven assembly are less critical and effects due to internal heating are reduced.
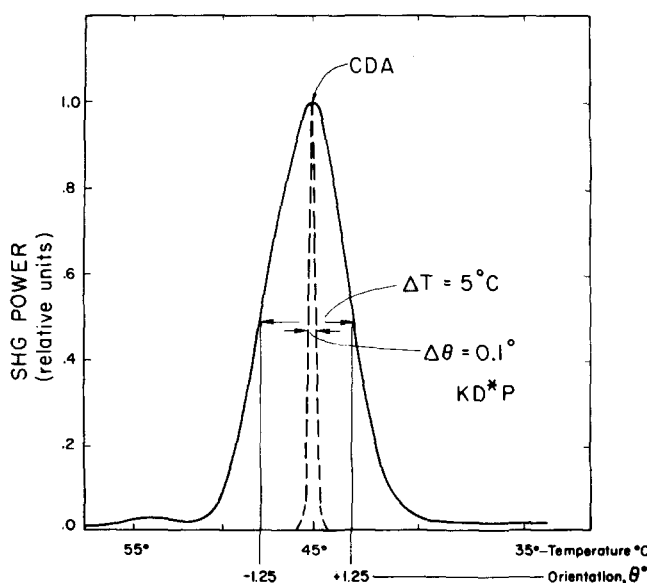
FIG. 3. Measured temperature and angular dependence of SH power due to the coefficient of nonlinear polarization d_{36} of CDA and KD*P for pump radiation at 1.062 μ.

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Broadband Efficient Excitation of the Thin-Ribbon Waveguide for Surface Acoustic Waves*

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A practical method for broadband efficient excitation of the thin-ribbon waveguide for surface acoustic waves is presented. Other major advantages of the excitation system are the simplicity of both its theoretical design and its practical implementation. Experimentally, a maximum excitation efficiency (power) of 65% has been obtained at an operating frequency of 5.5 MHz. In addition, the measured efficiency was in excess of 55% over the frequency range from 4.7 to 6.4 MHz.

The subject of waveguides for acoustic surface waves is still in its infancy, with most of the effort being expended in a search for suitable guiding structures and the understanding of their propagation characteristics. All of the waveguides proposed and investigated to date[1-6] are strictly laboratory prototypes on which measurements have been performed with little or no concern for the efficiency of excitation. To the best of our knowledge, the present investigation represents the first attempt to consider the problem of *efficiency* in connection with the excitation of surface acoustic waveguides, a problem which must certainly be resolved before the use of such waveguides can become practical.

The *principle* underlying the present technique for the efficient excitation of surface acoustic waveguides has recently been discussed in connection with its application to the coupling of optical beams to thin-film optical waveguides.[7] Only very recently, however, has the relevance of the same principle to the excitation of surface acoustic waveguides been recognized. The unifying feature of the above excitation schemes is the ability of the structure to support a leaky wave in the coupling (excitation structure) region. Briefly stated, the waveguide configurations are excited by sending in an incident beam of energy to couple into the leaky wave in the coupling region. The coupler is then truncated after an appropriate distance to yield the (nonleaky) surface-wave structure which was initially to be excited. As a result of this truncation, most of the leaky wave is then converted into the surface wave desired.

The conditions which maximize the excitation efficiency are derived in Ref. 7 in the context of optical waves, but the derivation there is sufficiently general to also cover the acoustic wave configuration considered here. The results of that derivation may therefore be em-

ployed directly for the present purposes. In order to maximize the excitation efficiency, it is shown in Ref. 7 that the beam should be incident at an angle θ which coincides with the direction of radiation of the leaky wave at the same frequency, and the beam width W should be chosen to satisfy the conditions that $\alpha W \sec \theta = 1.36$, where α is the leaky-wave attenuation constant.

Figure 1 shows the application of this excitation scheme to the thin-ribbon waveguide,[1,2] which consists of a thin strip of "slower" material deposited on a "faster" substrate. The modal fields of such a structure not only decay into the substrate, but also decay away transversely from either side of the ribbon, so that the energy is confined to the vicinity of the waveguide. The coupler for such a waveguide consists of the broad plated region separated from the waveguide by a cutoff gap of width d. (In practice, the plating is chosen to be
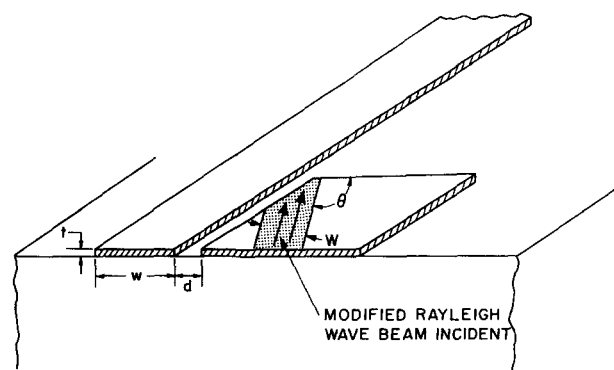

FIG. 1. Excitation of thin-ribbon waveguide.