locates the barrier outside of the GaInAs, somewhere within the Cs-O dipole structure. Other similar barriers have been postulated to be at the interface between the III-V semiconductor and a Cs_2O overlayer.[15] We suggest that the work described here may also furnish a physical basis for a barrier, but would place it within the GaInAs.

The authors are happy to acknowledge helpful and stimulating discussions with V. S. Ban, M. Ettenberg, and D. Richman.

[†]Work partially supported by the Advanced Research Projects Agency.
[1]J. J. Scheer and J. van Laar, Solid State Commun. **3**, 189 (1965).
[2]R. L. Bell, *Negative Electron Affinity Devices* (Clarendon, Oxford, 1973).
[3]This ternary is a completely miscible solid solution over the entire range $0 < x < 1$.
[4]Very kindly supplied by G. H. Olsen and T. J. Zamerowski.
[5]F. Jona, IBM J. Res. Develop. **9**, 375 (1965).
[6]F. Jona, J. Appl. Phys. **37**, 3637 (1966).
[7]At annealing temperatures above 600 °C there is less In diminution (as determined by Auger spectra), although the In evaporation rate (as determined by the QMA) continues to increase (see Fig. 2). This behavior suggests that at these higher temperatures, the process of In depletion at the surface may be limited by bulk diffusion.
[8]J. Comas and C. B. Cooper, J. Appl. Phys. **37**, 2820 (1966).
[9]The over-all sensitivity of the quadrupole mass analyzer decreases with increasing atomic mass.
[10]B. Goldstein and D. Szostak, Appl. Phys. Lett. **26**, 111 (1975).
[11]Interestingly, no trace of any oxide of In was detected in the desorption products of GaInAs.
[12]These figures may be somewhat lower if a degree of pseudomorphism is present in the In-depleted layer.
[13]D. G. Fisher, R. E. Enstrom, J. S. Escher, and B. F. Williams, J. Appl. Phys. **43**, 3815 (1972).
[14]J. J. Scheer and J. van Laar, Solid State Commun. **5**, 303 (1967).
[15]L. W. James and J. J. Uebbing, Appl. Phys. Lett. **16**, 370 (1970).

Third harmonic generation in phase-matched alkali metal vapors*

D. M. Bloom, G. W. Bekkers,† J. F. Young, and S. E. Harris

Microwave Laboratory, Stanford University, Stanford, California 94305
(Received 9 December 1974; in final form 3 February 1975)

We report improvements in conversion efficiency for third harmonic generation in sodium and rubidium vapor. 30-psec pulses of radiation at 1.064 μm have been converted to 0.3547 μm with an energy conversion efficiency of 10%. Factors limiting conversion efficiency are discussed.

PACS numbers: 42.65.F, 42.50.

Third harmonic generation in alkali metal vapors has been proposed[1] and demonstrated,[2] but until recently conversion efficiencies were limited to about 0.01%. In this letter we describe improvements in conversion efficiency; in particular, we have obtained 10% energy conversion efficiency for tripling of 1.064-μm radiation to 0.3547 μm in a phase-matched mixture of rubidium and xenon. These improvements have been achieved by increasing the metal vapor pressure, cell length, and power density. The maximum conversion efficiency obtained in these experiments was limited by experimental difficulties in obtaining higher metal vapor pressures. Improved understanding of pressure broadening indicates that breaking of phase matching by single-photon absorption, which was thought to impose the most severe limitation on conversion efficiencies,[3] will probably not be of consequence.

We have achieved phase matching by compensating the anomalous dispersion of the metal vapor by mixing it with a second positively dispersive gas at a ratio such that the index of refraction of the mixture was the same at the fundamental and the third harmonic.[1-3] Phase matching requires that the mixture be homogeneous over the total interaction length and typically requires temperature uniformity of ~0.5 °C. This mixture was obtained by making use of a concentric heat pipe oven[4] shown schematically in Fig. 1. The cell consisted of an inner stainless steel tube 2.5 cm in diameter and 1.5 m in length lined with an 80 mesh stainless steel screen with quartz windows on either end. The outer concentric chamber, also lined with stainless steel mesh, was 5 cm in diameter and 1 m long. Both chambers were loaded with about 100 g of alkali metal and connected to separate gas manifolds which allowed the buffer gas pressure in each chamber to be independently varied. In operation the buffer gas pressure of the outer chamber was fixed at the desired pressure of the metal vapor and the heater power was

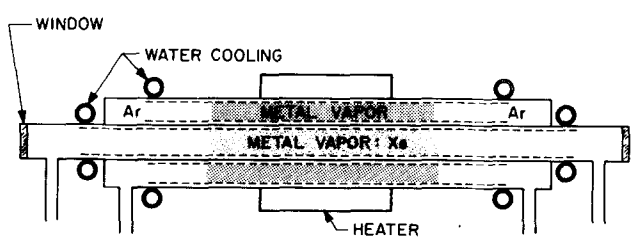

FIG. 1. Schematic of concentric heat pipe oven.

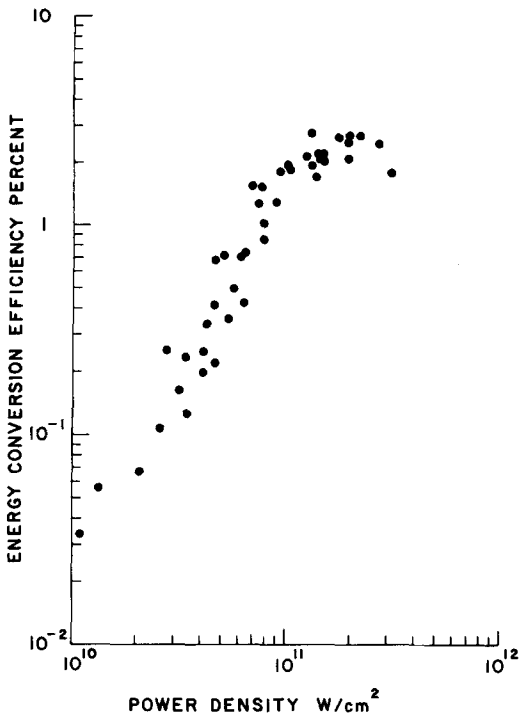

FIG. 2. Energy conversion efficiency vs incident power density for sodium (5-Torr sodium pressure, 40-cm zone length, beam area $=1.1\times10^{-3}$ cm^2).

adjusted to obtain a 50-cm-long column of boiling alkali metal. The boiling liquid in the outer chamber produced an isothermal zone along the inner chamber. The inner chamber was filled with xenon and since the same alkali metal was used in the inner and outer chambers, the partial pressure of the alkali metal vapor in the inner cell was the same as the total pressure of the outer chamber. The xenon pressure was adjusted during the experiments to maximize the third harmonic output. With heat pipe ovens of this type we have obtained phase matching of 100 coherence lengths, as determined by varying the xenon pressure and measuring the width of the phase matching curve. Strong convective flow in the temperature transition region has been a problem, causing condensation (fogging) at total inner cell pressures exceeding about 300 Torr. The insertion of apertures into the cell limiting the clear aperture to about 0.5 cm has somewhat alleviated the fogging problem allowing operation of the heat pipes to total pressures of about 800–1200 Torr.

For these experiments a single pulse selected from a passively mode-locked Nd:YAG oscillator was spatially filtered and amplified yielding a pulse 30 psec in duration with a peak power of about 3×10^8 W. The beam was focused into the heat pipe and the input 1.064-μm radiation and the generated third harmonic energy were measured with photodiodes calibrated on an average energy basis to an Eppley thermopile. The photodiode outputs were processed with sample and hold electronics and the third harmonic energy versus the incident 1.064-μm energy was point plotted on an X-Y plotter.

In the first experiment the laser was focused to a spot size of 1.1×10^{-3} cm^2 into a sodium concentric heat pipe oven operating at a sodium pressure of 5 Torr with a zone length of 40 cm. The results of this experiment are shown in Fig. 2. A maximum conversion efficiency of 2.7% was obtained at an input power density of 2×10^{11} W/cm^2 and a xenon-sodium ratio of about 150:1. At higher incident power densities the efficiency leveled off. This is believed to be due to multiphoton ionization of the sodium and should occur at the same power density regardless of the sodium pressure. In the second experiment the sodium oven was replaced with a similar cell containing rubidium operating at 3-Torr rubidium pressure and phase matched with about 1200-Torr xenon. The beam was initially focused to a spot size of 1.1×10^{-3} cm^2. Though conversion efficiency increased as the square of power density, at an incident density of about 10^{10} W/cm^2, self-focusing caused the 1.06-μm beam at the cell output to begin to expand. The incident beam was then refocused in an area of 1.1×10^{-2} cm^2. Figure 3 shows conversion efficiency as a function of power density. A conversion efficiency of 10% was obtained with relatively good beam quality. While self-focusing can be avoided by using larger beams, at higher vapor pressures the Kerr susceptibility also leads to breaking of phase matching. Though partially compensable, this may limit the conversion efficiency in rubidium. Theoretical calculations indicate that it will not be important in sodium.[3]

In the sodium and rubidium experiments maximum conversion efficiencies were obtained at energy densities of 6 and 0.24 J/cm^2, respectively. Using the pressure broadening data of Chen and Takeo[5] and taking into account the contribution of excited state atoms to

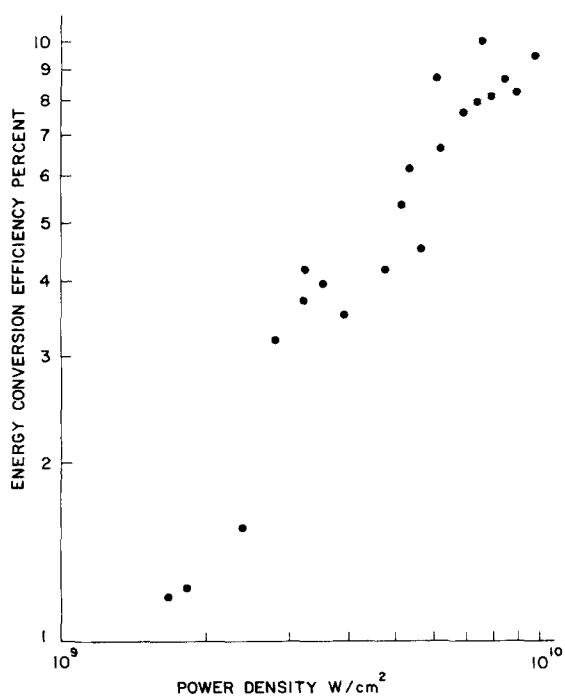

FIG. 3. Energy conversion efficiency vs incident power density for rubidium (3-Torr rubidium pressure, 50-cm zone length, beam area $=1.1\times10^{-2}$ cm^2).

the index of refraction, the theoretical maximum energy density is 0.95 J/cm^2 for sodium and 4.7×10^{-2} J/cm^2 for the cell lengths and pressures used in rubidium. No saturation was observed at energy densities 5–6 times above these values. The reason for these discrepancies is that the Lorentzian line shape which was used in the calculation of the theoretical values is not valid at the large detunings of these experiments. For detunings $\Delta\omega$ larger than $1/\tau_c$, where τ_c is the duration of a dephasing collision, the impact model for line broadening is no longer valid.[6] For large detunings the wing absorption is described by the quasistatic approximation.[6,7] In order to predict the far wing absorption it is necessary to accurately know the alkali metal–inert gas interaction potentials.[7] Since the detunings in these experiments exceed the potential well depths,[7] it is expected that the far wing absorption of the 1.064-μm radiation will be unimportant. While it now appears that the restrictions imposed on pulse length due to single photon absorption (at least at the fundamental wavelength) are eliminated, it should be pointed out that for pulses exceeding 1 nsec, avalanche breakdown may limit allowable energy densities, and necessitate longer cells for efficient tripling.

A principal limitation in the present experiment was the inability to increase the alkali metal vapor pressure. Higher pressures resulted in metal vapor condensation against the cold inert gas in the boundary layer regions. This difficulty may be overcome by choosing a more dispersive phase-matching gas. The substitution of a second metal vapor such as magnesium, in place of the xenon, would reduce the phase-matching ratio from 152:1 to 0.84:1 and allow the alkali metal vapor pressure to be increased. Homogeneous mixtures of these metal vapors should be obtainable by making use of a two-metal heat pipe oven.[8] A second approach would be to enhance the nonlinearity by choosing a laser frequency whose third harmonic was closer to an allowed transition. For instance, the 1.074-μm line of Nd:YAG has a third-order nonlinearity in rubidium 4–5 times larger than that for 1.064 μm. A third approach would be to use a noncollinear phase-matching technique. By splitting the beam into three beams and intersecting them at a small angle in a cell containing pure alkali metal vapor, phase synchronism between the driving polarization and the third harmonic field can be achieved. This approach would require larger beams and thus higher power in order to maintain beam overlap. Experiments to demonstrate some of these ideas are underway in our laboratory.

We gratefully acknowledge helpful discussions with M. M. Hessel and A. H. Kung.

*Research supported by the University of California, the Atomic Energy Commission and the National Aeronautics and Space Administration under Contract NGL-05-020-103.

†On leave from IBM, San Jose, under the Resident Study Program.

[1]S. E. Harris and R. B. Miles, Appl. Phys. Lett. **19**, 385 (1971).
[2]J. F. Young, G. C. Bjorklund, A. H. Kung, R. B. Miles, and S. E. Harris, Phys. Rev. Lett. **27**, 1551 (1971).
[3]R. B. Miles and S. E. Harris, IEEE J. Quantum Electron. **QE-9**, 470 (1973).
[4]C. R. Vidal and F. B. Haller, Rev. Sci. Instrum. **42**, 1779 (1971).
[5]S. Chen and M. Takeo, Rev. Mod. Phys. **29**, 20 (1957).
[6]W. R. Hindmarsh and Judith M. Farr, *Progress in Quantum Electronics*, Vol. 2, Part 3, edited by J. H. Sanders and S. Stenholm (Pergamon, New York, 1972).
[7]W. E. Baylis, J. Chem. Phys. **51**, 2665 (1969).
[8]C. R. Vidal and M. M. Hessel, J. Appl. Phys. **43**, 2776 (1972).

TeO_2 anisotropic Bragg light deflector without midband degeneracy

T. Yano, M. Kawabuchi, A. Fukumoto, and A. Watanabe

Matsushita Research Institute Tokyo, Inc., Ikuta, Kawasaki, Kanagawa, Japan
(Received 3 February 1975; in final form 7 April 1975)

An advanced acousto-optic light deflector has been designed using the acoustic shear wave traveling slightly off the [110] axis in TeO_2. The midband mode degeneracy reported by Warner *et al.*, which decreases the diffracted light intensity, has been shifted off from the active frequency region. A linearly polarized wave can be used as the incident light instead of the elliptically polarized wave used in the conventional deflector designed by Warner *et al.* The deflector yields a larger number of resolvable spots due to the broadened bandwidth. Experimentally, with 6328-Å light, a 3-dB bandwidth of 50 MHz was observed with a diffraction efficiency of 80% and an electric power of 350 mW. The new deflector has a capacity of 500 resolvable spots with a random access time of 10 μsec.

PACS numbers: 42.80.E, 78.20.H

The first light deflector using TeO_2 was reported by Uchida *et al.*[1] At that time, the extremely high acousto-optic efficiency[2] was revealed for the interaction employing the slowest shear sound wave along the [110] direction. A second unique light deflector using TeO_2 was designed by Warner *et al.*,[3] where widening of the frequency bandwidth was achieved by introducing anisotropic Bragg diffraction into the first type deflector.