Sum frequency generation of sodium resonance radiation

Thomas H. Jeys, A. A. Brailove, and Aram Mooradian

We have generated pulsed, high power, sodium resonance radiation by sum frequency mixing the 1.06 μm and 1.32 μm outputs of two Nd:YAG lasers with an average power conversion efficiency of 30%. The wavelength of the sum radiation was tuned across the full Doppler width of the sodium-vapor D_2 absorption by tuning the wavelength of either Nd:YAG laser with intracavity etalons. The wavelength of the 1.32 μm Nd:YAG laser was also tuned by injection seeding with a GaInAsP/InP diode laser. We have used this sodium resonance radiation for the lidar observation of the earth's naturally occurring atomic–sodium layer at 90 km altitude.

An interesting coincidence of nature is that the sum frequency of two appropriately tuned Nd:YAG lasers, one operating near 1.06 μm and the other operating near 1.32 μm, may be made resonant with the sodium D_2 transition wavelength.[1] This source of sodium resonance radiation has several advantages over the more commonly used dye lasers. It can be scaled more easily and reliably to high peak powers with high beam quality, and for some applications[2] has the potential for all solid-state operation. The spectral content of the sum radiation may be made to cover more uniformly the sodium Doppler-broadened absorption profile. In addition, the sum frequency may be tuned by tuning the frequency of an injection-seeding diode laser.

A schematic of the apparatus for sum frequency generation of sodium resonance radiation is shown in Fig. 1. The outputs of the two Nd:YAG lasers were made to propagate coaxially using a dichroic mirror and then focused into a 5-cm-long lithium–niobate crystal held at the phase-matching temperature of 224°C. The sum radiation, generated in the crystal, was then directed into a sodium-vapor cell where resonance fluorescence was observed whenever the sum radiation was tuned to the sodium D_2 transition. The wavelength tuning curves of the 1.06 μm and 1.32 μm Nd:YAG laser transitions, using solid intracavity tiltable etalons, are shown in Fig. 2. The 1.06 μm laser had a tuning range of ~6 Å, while the 1.32 μm laser had a tuning range of ~5 Å. By operating the lasers near the center of their tuning ranges as indicated by the arrows in Fig. 2 (1.064591 μm and 1.319250 μm) it was possible to generate sodium resonance radiation (0.589159 μm). In addition, it was possible to tune the sum radiation over a 3 Å range, nearly centered at the sodium D_2 transition, easily encompassing the Doppler-broadened, sodium vapor absorption profile of 0.03 Å (3 GHz) width. Since the sodium D_1 transition is nearly 6 Å from the sodium D_2 transition it was not possible to generate radiation resonant with the D_1 transition. (The D_1 and D_2 could both be reached using the larger 1.06 μm tuning range of a Nd:glass laser.)

The spectral content of the Nd:YAG lasers as well as the sum radiation were monitored with separate Fabry-Perot spectrum analyzers. The typical spectral output of the lasers when operated continuously in the TEM_{00} mode is shown in Fig. 3. Both the 1.06 μm and 1.32 μm Nd:YAG lasers usually operated on three adjacent longitudinal cavity modes. The sum radiation then consisted of 9 (3×3) separate frequencies with a spectral range equal to the sum of the Nd:YAG laser spectral ranges and with a frequency density greater than either Nd:YAG laser. The higher frequency density of the sum radiation is important for uniform spectral coverage of the Doppler-broadened sodium spectrum. Complete frequency coverage of the sodium spectrum should be possible by operating each Nd:YAG laser over a broad spectral range, through intracavity frequency modulation,[3] such that the cavity frequency interval of the two lasers differ by the sodium natural linewidth of 10 MHz. Under these conditions it should be possible to generate sodium resonance radiation at intervals of 10 MHz over the full Doppler-broadened absorption profile. In order to obtain such complete spectral coverage from a dye laser, the dye laser cavity must be very long (15 m).[4]

When this work was done all authors were with MIT Lincoln Laboratory, Lexington, Massachusetts 02173-0073; A. A. Brailove is now with Massachusetts Institute of Technology, Cambridge, Massachusetts 02179.

Received 10 November 1988.
0003-6935/89/132588-04$02.00/0.

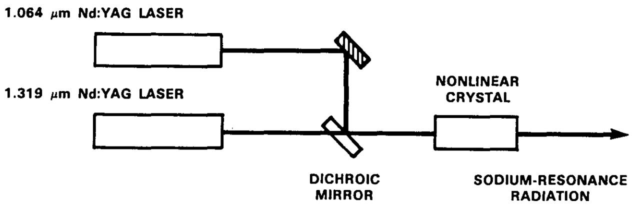

Fig. 1. Schematic of the laser system for sum frequency generation of sodium resonance radiation. The Nd:YAG lasers contained etalons for wavelength tuning and acousto-optic modulators for Q-switching the laser radiation. The 1.064 μm Nd:YAG laser operated with a 10% output coupler while the 1.319 μm Nd:YAG laser operated with a 3% output coupler.

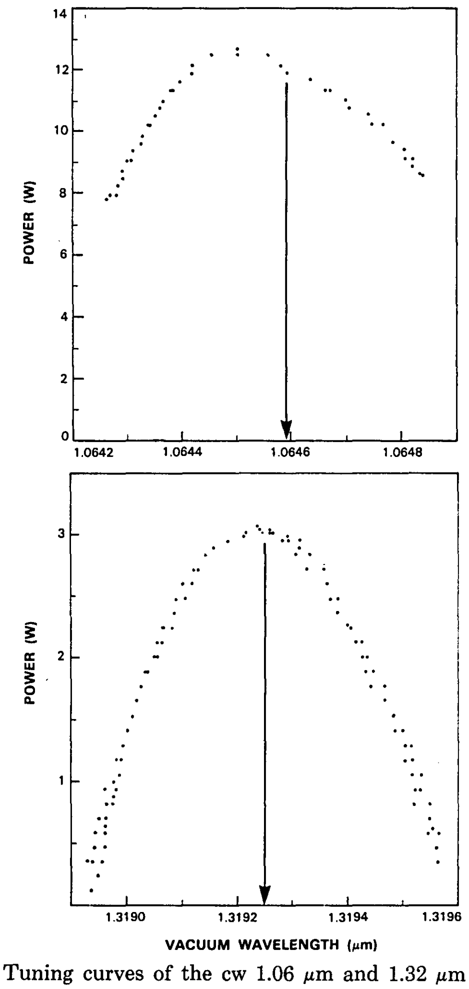

Fig. 2. Tuning curves of the cw 1.06 μm and 1.32 μm Nd:YAG lasers. Each laser was polarized and operated continuously in the TEM_{00} spatial mode. The wavelength of each laser was tuned by manually tilting solid intracavity etalons which were coated for 15% reflectivity per surface. The 1.06 μm laser was tuned with a 0.5 mm thick etalon and the 1.32 μm laser was tuned with a 0.2 mm thick etalon. The absolute wavelengths were measured by a vacuum wavemeter. The 1.32 μm Nd:YAG laser cavity was purged with nitrogen gas in order to eliminate water vapor absorption lines which significantly suppressed the long wavelength end of the tuning curve, and prohibited the laser from operating at 1.31935 μm, 1.31941 μm, and 1.31949 μm. Sodium resonance radiation was generated by sum frequency mixing radiation with wavelengths indicated by the arrows.

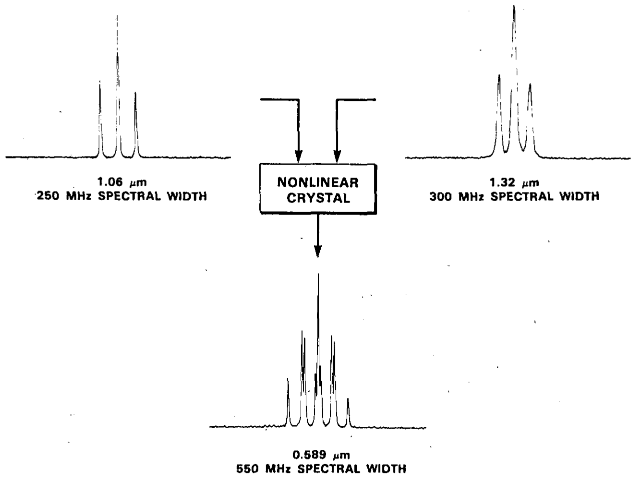

Fig. 3. Frequency spectra of the cw Nd:YAG laser radiation and the sum radiation as measured by three Fabry-Perot spectrum analyzers. The lasers and sum radiation spectra were measured by confocal Fabry-Perot spectrum analyzers, each with a free spectral range of 2 GHz and a finesse of about 200. The measured linewidth of each frequency is limited by the finesse of the spectrum analyzer. The 1.06 μm and 1.32 μm Nd:YAG lasers had cavity mode frequency intervals of 125 MHz and 150 MHz, respectively, while the sum radiation had an average frequency interval of 61 MHz and a minimum frequency interval of 25 MHz (150 MHz–125 MHz).

When the Nd:YAG lasers were Q-switched at a 1 kHz repetition rate, the 1.064 μm laser had an average output power of 900 mW within a 1 GHz spectral range, the 1.319 μm laser had an average output power of 880 mW within a 1 GHz spectral range, and the 0.589 μm radiation had an average power of 395 mW within a 2 GHz spectral range. The 1.06 μm and 1.32 μm lasers had Q-switched pulse lengths of 100 and 200 ns, respectively, while the sum radiation had a pulse length of 100 ns. The high index of refraction (2.23) of lithium niobate resulted in a 14% reflection of the Nd:YAG and sum frequency radiation at the uncoated crystal surfaces. After accounting for these losses we conclude that the average intracrystal frequency mixing efficiency was 30% while the peak efficiency was ~40%. These efficiencies were limited by incomplete temporal and spatial overlap of the Nd:YAG laser beams in the lithium–niobate crystal. Even higher mixing efficiencies should be possible by simultaneously mode-locking and Q-switching the Nd:YAG lasers.

In addition to lithium niobate ($LiNbO_3$), we have also sum frequency mixed the 1.06 μm and 1.32 μm Nd:YAG laser radiations in potassium titanyl phosphate (KTP) and lithium iodate ($LiIO_3$). Like lithium niobate, KTP also has a high nonlinear coefficient. Our crystal of KTP was 4 mm in length and therefore less efficient for sum frequency generation than the 5-cm-long lithium–niobate crystal. Although lithium iodate has a much smaller nonlinear coefficient than lithium niobate its optical damage threshold is much greater. Unfortunately, lithium iodate cannot be colinearly phase matched for sum frequency generation of sodium resonance radiation (about 4° walkoff) and phase matching occurs over a very narrow range of angles (0.4 mr cm). Lithium niobate proved to be the best of the three crystals for sum frequency mixing of

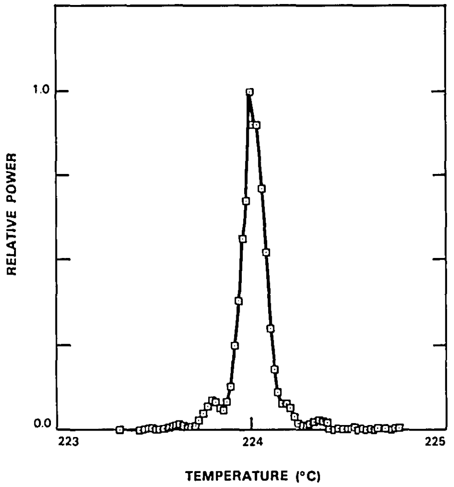

Fig. 4. Temperature dependence of the sum frequency generation of sodium resonance radiation in a 5-cm-long crystal of lithium niobate.

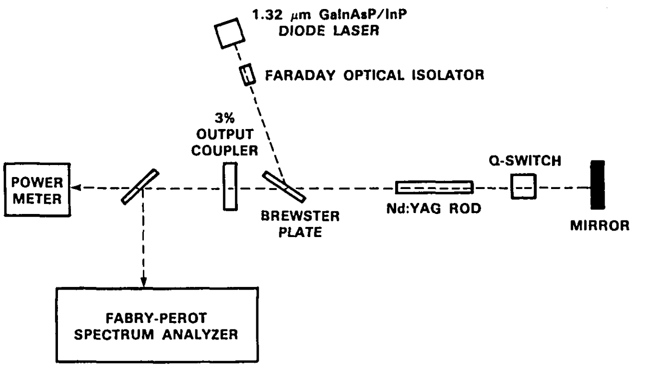

Fig. 5. Injection seeding of a Q-switched 1.319 μm Nd:YAG laser with the output of a GaInAsP/InP diode laser. The diode-laser radiation was injected into the Nd:YAG laser via the Brewster plate while the Faraday optical isolator served to protect the diode laser from the high power Nd:YAG laser radiation. The Q-switched Nd:YAG laser operated with an average power of 1 W, a pulse repetition rate of 1 kHz, and a pulse width of 3 μs. The 1.32 μm Nd:YAG laser used in the injection-seeding study was not the same laser as that used in the sum frequency mixing or lidar study.

our cw-pumped Q-switched Nd:YAG laser beams. Since lithium niobate may be noncritically phase matched by temperature tuning, the sum radiation propagated collinearly with the Nd:YAG laser radiation and had nearly diffraction-limited beam quality. The problems associated with the use of lithium niobate were its sensitivity to temperature which required careful temperature control of the crystal and its low optical damage threshold. As can be seen in Fig. 4, optimal sum-frequency mixing occurs within a 0.1°C temperature range in the vicinity of 224°C. The power oscillation to each side of the optimum crystal temperature is a result of the $(\sin(x)/x)^2$ dependence of the sum frequency generation process and indicates that the entire crystal had a nearly uniform temperature distribution. We saw no evidence of photorefractive damage[5] to which lithium niobate is susceptible at lower temperatures.

By injection seeding a 1 kHz Q-switched 1.32 μm Nd:YAG laser with the output of a GaInAsP/InP diode laser, the wavelength and spectral range of the 1.32 μm Nd:YAG laser, and, in turn, that of the sum radiation, may be controlled. Figure 5 shows a schematic of the Nd:YAG laser cavity and diode laser injection-seeding configuration. The GaInAsP/InP diode laser[6] operated with a total output power of 3 mW on three longitudinal modes separated by 10 Å. Since the intermode spacing of the diode laser was greater than the gain bandwidth of the 1.32 μm Nd:YAG laser, only one mode of the diode laser fell within the gain region of the Nd:YAG laser. With no intracavity frequency selective elements, the injection of as little as 10^{-8} W of diode laser radiation narrowed the spectral range of the Q-switched Nd:YAG laser from >8 GHz to ≈340 MHz, consisting of three simultaneously seeded longitudinal modes. By either current or temperature tuning the diode laser output frequency, the central operating frequency of the Q-switched Nd:YAG laser could be tuned over a 16 GHz range. Injection seeding was maintained over all of this tuning range since the 400 MHz natural phase fluctuation linewidth of the diode-laser radiation was greater than the cavity-mode spacing of the Nd:YAG laser. In addition, by bistably current tuning the diode laser between each Nd:YAG pulse we have switched the central operating frequency of each Nd:YAG laser pulse by as much as 10 GHz.

We have also observed resonance fluorescence from the earth's sodium layer[7] using this source. Sodium resonance radiation with an average power of 300 mW, a repetition rate of 1 kHz, and a pulse length of 100 ns was transmitted into the atmosphere coaxial with the field of view of a Cassegrainian telescope. This telescope had an aperture of 583 cm^2 and a field of view slightly larger than the 1 mrad divergence of the sodium resonance radiation. The radiation backscattered by the earth's atmosphere was collected by the telescope and then passed through a 80 Å-wide interference filter and polarizer for background reduction. The radiation was detected by a photomultiplier tube. The photomultiplier counts were recorded by a multichannel scaler as a function of the elapsed time after the sodium resonance radiation was transmitted into the atmosphere. Figure 6 shows the signal received from the earth's upper atmosphere. The signal at early times, results from Rayleigh scattering in the atmosphere while the peak at 600 μs corresponds to resonant backscattering from the sodium layer. These data were taken by integrating all the photocounts received over a ½ hour time span during the evening of 25 August 1987.

We have demonstrated the efficient generation of sodium resonance radiation by sum frequency mixing the output of two Nd:YAG lasers, one operating at 1.06 μm and the other operating at 1.32 μm. The frequency of the sum radiation may be tuned across the sodium D_2 Doppler-broadened transition either by the conventional tilting of an intracavity etalon or by tuning the frequency of a diode laser being used to injection

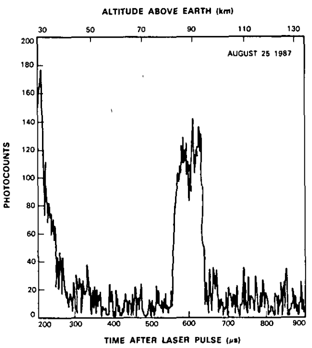

Fig. 6. Sodium resonance radiation backscattered by the earth's atmosphere. Photomultiplier counts per μs are plotted as a function of the elapsed time after the sodium resonance radiation pulse is transmitted into the atmosphere. The signal from the mesospheric sodium layer occurs at a round-trip time of 600 μs.

seed the 1.32 μm Nd:YAG laser. The spectral distribution of the sum radiation across the Doppler-broadened absorption profile may easily be made more uniform than that of conventional dye lasers.

We thank W. E. Defeo, D. K. Killinger and J. Harrison for their advice and assistance during the course of this work. In addition we thank J. N. Walpole and L. J. Missaggia for providing the diode lasers used in this work.

This work was supported by the Defense Advanced Research Projects Agency.

References

1. T. H. Jeys, D. K. Killinger, J. Harrison, and A. Mooradian, "Nd:YAG Sum-Frequency Generation of Sodium Resonance Radiation," in *Technical Digest of Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 1987), paper WE6.
2. C. S. Gardner, J. L. Bufton, and C. R. Philbrick, "Compact Shuttle Lidar for Global Observations of Atmospheric Waves in the Mesospheric Sodium Layer," in Technical Digest of Topical Meeting on Optical Remote Sensing of the Atmosphere, (Optical Society of America, Washington, DC, 1985), paper WC29.
3. D. J. Kuizenga and A. E. Siegman, "FM-Laser Operation of the Nd:YAG Laser", IEEE J. Quantum Electron. **QE-6,** 673–677 (1970).
4. J. Liang and C. Fabre, "Modification of the Velocity of Atoms Submitted to a Resonant Multimode Laser: An Experimental Study," Opt. Commun. **59,** 31–35 (1986). J. Liang, L. Moi, and C. Fabre, "The 'Lamp Laser': Realization of a Very Long Cavity Dye Laser," Opt. Commun. **52,** 131–135 (1984). L. Moi, "Application of a Very Long Cavity Laser to Atom Slowing Down and Optical Pumping", Opt. Commun. **50,** 349–352 (1984).
5. A. M. Glass, "The Photorefractive Effect," Opt. Eng. **17,** 470–479 (1978).
6. Z. L. Liau, J. N. Walpole, and D. T. Tsang, "Low Threshold GaInAsP/InP Buried-Heterostructure Lasers with a Chemically Etched and Mass-Transported Mirror," Appl. Phys. Lett. **44,** 945–947 (1984).
7. E. S. Richter, J. R. Rowlett, C. S. Gardner, and C. F. Sechrist, Jr., "Lidar Observation of the Mesospheric Sodium Layer Over Urbana Illinois," J. Atmos. Terr. Phys. **43,** 327–337 (1981). C. S. Gardner, and D. G. Voelz, "Lidar Measurements of Gravity Wave Saturation Effects in the Sodium Layer," Geophys. Res. Lett. **12,** 765–768 (1985).