Potential for coherent Doppler wind velocity lidar using neodymium lasers

Thomas J. Kane, Bingkun Zhou, and Robert L. Byer

Existing techniques for the frequency stabilization of Nd:YAG lasers operating at 1.06 μm, and the high-gain amplification of radiation at that wavelength, make possible the construction of a coherent Doppler wind velocity lidar using Nd:YAG. Velocity accuracy and range resolution are better at 1.06 μm than at 10.6 μm at the same level of the SNR. Backscatter from the atmosphere at 1.06 μm is greater than that at 10.6 μm by ~2 orders of magnitude, but the quantum-limited noise is higher by 100 also. Near-field attenuation and turbulent effects are more severe at 1.06 μm. In some configurations and environments, the 1.06-μm wavelength may be the better choice, and there may be technological advantages favoring the use of solid-state lasers in satellite systems.

I. Introduction

It is possible to measure a velocity component of the wind by measuring the Doppler shift of electromagnetic radiation scattered by particles entrained in the wind. Microwave radar systems at a wavelength of 10 cm provide data on the structure and development of storms using raindrops as the scattering particles.[1] Microwave radar systems can also detect and interpret signals arising from reflections taking place due to density fluctuations in clear air.[2] Laser radar systems operating at the 10.6-μm carbon dioxide laser line have successfully measured the wind velocity by detecting the radiation scattered from dust particles (aerosols), which are found even in the clearest atmospheric air.[3] The technology of wind velocity measurement using CO_2 lasers has developed to the point where a mobile system has been built to study the adequacy of the return signal in different geographical regions. The possibility of installing such a system on a satellite or space shuttle is being seriously considered.[4]

These microwave and far-IR systems are described as coherent systems because their operation requires a comparison of the phase of the scattered signal with the phase of a reference signal at the detector. This reference signal must have good frequency stability (or coherence) if the system is to be accurate. Coherent microwave and far-IR systems generally transmit short pulses and achieve range resolution by measuring the time delay of the return signal. Only the component of wind velocity parallel to the beam is measured in this type of system.

In this paper we examine the potential for remote wind sensing lidar systems based on neodymium lasers. We show that at a given level of the SNR, the 1.06-μm wavelength of Nd:YAG offers smaller velocity error and better range resolution than is possible using the 10.6-μm wavelength of CO_2 lasers. Currently available data indicate that at similar levels of transmitted power, the SNR at 1.06 μm for typical atmospheric conditions is the same as the SNR at 10.6 μm, if the effects of atmospheric turbulence are not considered. Atmospheric turbulence is a greater problem at 1 μm than at 10 μm, but for some system configurations it is not an important problem for either wavelength.

Neodymium solid-state systems may offer technological advantages compared with CO_2 laser-based systems. The rapid progress in high-power diode semiconductor lasers may lead to diode-pumped Nd:YAG systems, which are more efficient than CO_2 lasers and offer longer operating lifetimes for satellite-based measurements. Finally, we briefly describe the Nd:YAG-based remote wind sensing lidar under construction at Stanford University.

II. Velocity Estimate Error

The pulse pair algorithm is a well-understood way to extract an estimate of average frequency (and thus velocity) from a random signal with a Gaussian-shaped spectrum.[5] For a particular SNR the expected rms velocity error is given by

$$\delta v = \frac{\lambda}{4\pi}\left(\frac{f}{2NLt}\right)^{1/2}\left(2\pi^{3/2}W + \frac{16\pi^2W^2}{\mathrm{SNR}} + \frac{1}{\mathrm{SNR}^2}\right)^{1/2}, \quad (1)$$

The authors are with Stanford University, Edward L. Ginzton Laboratory, Stanford, California 94305.

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where f is the sampling frequency, N is the number of pulses averaged, t is the duration of a transmitted pulse, L is the ratio of the length of a range gate to the length of a pulse, and λ is the wavelength.[6] The value W is a measure of the frequency spread of the return signal in the absence of any noise and is given by

$$W = \frac{1}{v_{\mathrm{Ny}}} (v_{bw}^2 + v_{\mathrm{atm}}^2)^{1/2}, \tag{2}$$

where v_{Ny} is the maximum unaliased velocity as determined by the Nyquist criterion, $v_{\mathrm{Ny}} = f\lambda/2$, v_{bw} is the velocity uncertainty corresponding to the bandwidth of the transmitted pulse, and v_{atm} is the standard deviation of the velocity distribution in the measured volume due to turbulence and wind shear. Note that for a fixed value of v_{Ny} the shorter wavelength will require a proportionally faster sampling frequency f. For a Fourier transform-limited Gaussian pulse, the spread due to bandwidth is given by $v_{bw} = \lambda/4\pi t$.

The effect of wavelength on velocity error depends on the other parameters involved. We present a few examples. If the SNR is fixed, the 1-μm system always gives a smaller velocity uncertainty. However, the size of the advantage varies from case to case. The 1-μm wavelength is also able to provide greater spatial resolution. We examine velocity error and spatial resolution for four cases: that of error dominated by wind variability v_{atm}, by pulse length v_{bw}, by noise with low SNR, and by noise with moderate SNR.

A. High SNR: Wind Variability Dominates Error

In the regime where the predominant source of error is the range of velocities in the measured volume and the average velocity is desired, the expected error in the average velocity simplifies to

$$\delta_v = (2\pi^{3/2} v_{\mathrm{atm}} \lambda / NLt)^{1/2} / 4\pi. \tag{3}$$

With all other factors held constant, the velocity error at 1 μm is less than that at 10 μm by a factor of the square root of 10. This improvement is due to the observation of more full cycles of the return signal from a particular range gate at 1 μm than at 10 μm because of the greater Doppler shift. The mean square fractional frequency error decreases with the number of cycles counted. A useful figure of merit is the product of the velocity variance δv^2 and the range resolution given by $\delta R = cLt/2$, where c is the speed of light. Ignoring constant factors, this yields

$$\delta v^2 \delta R \propto v_{\mathrm{atm}} \lambda / N. \tag{4}$$

A ten times better range resolution is possible at 1 μm than at 10 μm, with velocity error held constant.

B. High SNR: Transmitted Pulse Bandwidth Dominates Error

If the SNR is high and high-range resolution is desired, the frequency uncertainty due to the limited pulse duration becomes the predominant error source. This case yields the same uncertainty relations that apply to nonstochastic hard targets. The equation for the velocity uncertainty becomes

$$\delta v = \lambda (\pi^{1/2}/2NL)^{1/2} / 4\pi t. \tag{5}$$

The velocity resolution at 1 μm is 10 times better than at 10 μm for this case. The product of range resolution and velocity resolution becomes, ignoring constant factors,

$$\delta v \delta R \propto \lambda (L/N)^{1/2}. \tag{6}$$

The advantage of a shorter wavelength is greater in the case of nonrandom targets. In this case it is not the mean square error but the rms error that increases linearly with wavelength.

C. Low SNR

When the SNR is very low (of the order of 1) it is the last term of Eq. (1) that dominates. In this case the velocity uncertainty becomes

$$\delta v = \lambda (f/2NLt)^{1/2} / 4\pi \mathrm{SNR}. \tag{7}$$

Since the sampling frequency f must be greater at shorter wavelengths for the same maximum velocity, as determined by the Nyquist criterion, this equation is more useful for comparison if written in terms of the maximum velocity $v_{\mathrm{Ny}} = f\lambda/2$. Equation (7) then becomes

$$\delta v = (\lambda v_{\mathrm{Ny}}/NLt)^{1/2} / 4\pi \mathrm{SNR}. \tag{8}$$

Once again the velocity resolution is better at 1 μm than at 10 μm by a factor of the square root of 10. A lower SNR at 1 μm can yield the same velocity error. The range resolution–velocity resolution trade-off, again dropping constants, is

$$\delta v^2 \delta R = \frac{\lambda v_{\mathrm{Ny}}}{N \cdot \mathrm{SNR}^2} \tag{9}$$

D. Intermediate Case: Moderate SNR

In the case of moderate SNR, Eq. (1) cannot be written simply. All terms contribute to the velocity error. However, a few comments can be made.

The velocity error advantage at 1 μm is between 10 and the square root of 10. The advantage in range resolution, other things held constant, is in all cases a factor of 10.

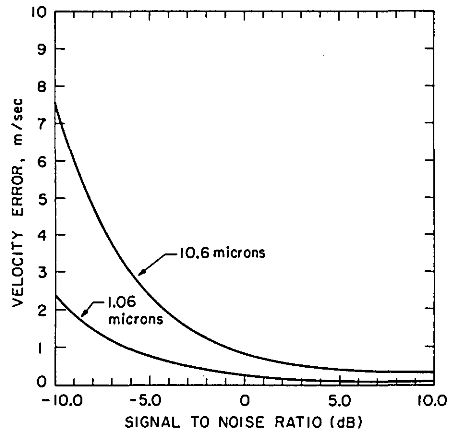

Fig. 1. Expected velocity error plotted as a function of SNR. Both pulse length and range gate are 3 μsec. Maximum unaliased velocity v_{Ny} is 25 m/sec, and rms wind variability v_{atm} is 0.3 m/sec. Error at 10.6 μm is slightly more than $\sqrt{10}$ times as high as error at 1.06 μm.

If a particular maximum velocity error is acceptable, a measurement at 1 μm can be made at a lower SNR than is possible at 10 μm. At low SNR the 1-μm SNR can be lower by $\sqrt{10}$. At higher SNR, the velocity resolution degrades more slowly as the SNR goes down, and the allowable SNR reduction possible at 1 μm is in all cases $>\sqrt{10}$.

Figure 1 is a plot of an expected single-pulse velocity error calculated using Eq. (1). The pulse length and range gate are both 3 μsec. The value of v_{Ny} is 25 m/sec, and the rms wind variability v_{atm} is 0.3 m/sec. For this case the ratio of the errors is $\sim\sqrt{10}$ at all values of SNR. For shorter pulse length or less wind variability the advantage of 1.06 μm compared with 10.6 μm is larger.

III. Signal-to-Noise Considerations

A. Atmospheric Beta

The backscatter cross section of a sphere of known radius and index of refraction can be calculated exactly. In the Rayleigh scattering limit, when the size of the wavelength is large compared with the size of the scattering sphere, the backscatter cross section is proportional to the inverse fourth power of the wavelength. If all aerosol particles were small compared with 1 μm, the value of β, the backscatter cross section per unit volume of air, would be 10,000× higher at 1 μm than at a wavelength of 10 μm.

In fact the particles containing the greatest fraction of the aerosol mass are near 1 μm in radius, and the advantage at 1 μm is considerably less than 10,000. Kent estimates that the typical ratio of backscatter at 1 μm to backscatter at 10 μm is in the 40–200 range for air in the free troposphere.[7] The backscatter at 10 μm is a very sensitive function of the number of fairly large particles (>1 μm),[8] and thus it is the more variable of the two values. For tropospheric air over the oceans, and in the stratosphere during times of volcanic inactivity, the advantage at 1 μm will be as high as 200. This is significant because these are the conditions that would result in very low return signals at 10 μm.

The statistical distribution of β values, for different altitudes and regions, is not known well. As data from the SAGE and SAM II satellite sensors become available,[9] much more will be known about atmospheric attenuation (and thus backscatter) at 1 μm. It is approximately true that in the troposphere the backscatter from aerosols at 1 μm is the same as the backscatter from the air itself (molecular backscatter).[10] This value is $3 \times 10^{-8}\ \mathrm{m}^{-1}$ for air at 0°C and 1-atm pressure. Very clean air would have a backscatter value due to aerosols of $10^{-9}\ \mathrm{m}^{-1}$.

B. Coherence of Return Signal

For minimum background interference, the detected signal must be collected from a single diffraction-limited spot on the focal plane of the telescope. If the source of the collected light were a fixed point at infinity, such as a star, the amount of light collected in a single diffraction-limited spot would be severely limited by the optical distortion caused by the turbulent atmosphere. In the visible, during times of moderate turbulence, it becomes impossible to increase the power collected in a single spatial mode once the diameter of the telescope exceeds a few centimeters. This would also be the case for a bistatic laser radar system. Clifford and Lading[11] have shown that for a system where the same optics are used for both transmission and collection of the signal (a monostatic system), moderate turbulence is less of a disadvantage. Without turbulence, a system collecting light in a single spatial mode receives a signal strongly peaked at the focus of the telescope and attenuated at both shorter and longer ranges. This effect leads to received powers a few orders of magnitude greater at the focus than at close range. The effect of moderate turbulence is to reduce the signal from the focal volume but to increase the signal from closer range.

Turbulence is a potentially important parameter at $\lambda = 1.06$ μm, especially for ground-based systems. The transverse atmospheric coherence length ρ_0 has a $\lambda^{6/5}$ dependence. Thus ρ_0 at 10.6 μm is 15.8× larger than at 1.06 μm. A reasonable approximation for SNR reduction due to turbulence in the focused beam case is

$$F_0 = 1/(1 + D^2/4\rho_0^2), \tag{10}$$

where D is the optics diameter and F_0 is the SNR reduction factor relative to the zero turbulence case.[12] Consider the case where ρ_0 computed for 10.6 μm is equal to the telescope diameter D. The value of F_0 is 0.8. Using the scaling law for ρ_0 mentioned above, the value of F_0 at 1.06 μm is 0.015.

The problem of near-field attenuation of the signal received by diffraction-limited systems is also greater since the area of a diffraction-limited spot for 1-μm radiation is 1/100 the area of a diffraction-limited spot for 10-μm radiation. It may be desirable to detect more than a single spatial mode of the return signal at 1 μm.

In some configurations the effects of turbulence and near-field attenuation are greatly reduced. One example is a system with a small aperture telescope. Another is the case of a telescope above the atmosphere. It is turbulence immediately in front of the telescope that is responsible for most of the reduction in signal. Turbulence in the scattering volume has no effect, since the scattering process is incoherent. Near-field attenuation is not a problem for a satellite-based system, since the signal from the near field is not of interest.

C. Noise

Quantum-limited noise levels have been achieved for coherent detection of 10-μm radiation. At 1 μm, reaching this limit is much easier due to the lower detector dark current and greater amount of quantum noise. The quantum noise is given by

$$N = Bh\nu, \tag{11}$$

where B is the detection system bandwidth, and $h\nu$ is the energy of a single photon at the wavelength of interest. At 1 μm the photon energy is 10× greater and the bandwidth 10× larger for the same range of velocities. Thus the noise is 100× greater at 1 μm than at 10 μm for quantum-limited detection.

As stated above, the atmospheric β and thus the signal at 1.06 μm are ~40–200× that at 10.6 μm. The quantum-limited noise at the shorter wavelength is 100× as great as that at the CO_2 wavelength. The result is that the SNR at 1.06 μm will typically be about the same as that at 10.6 μm. In very clear air, the SNR at 1 μm will exceed that at 10 μm.

IV. Energy Requirements—Ideal Case

The transmitted energy needed to receive a signal equal to the noise can be calculated if losses due to turbulence and collection inefficiency are neglected. The basic equation for the SNR is

$$\mathrm{SNR} = \eta\lambda\beta E\pi d^2/8R^2Bh, \tag{12}$$

where η = detection efficiency,
E = pulse energy,
d = telescope diameter,
R = range of return signal with telescope focused there,
B = system bandwidth, and
h = Planck's constant.

First, we calculate the minimum value of β for the moderate-sized ground-based system under construction at Stanford. We assume optimal conditions with no loss due to turbulence. We also assume 100% collection and detection efficiency, quantum-limited detection, a transmitted pulse energy of 100 mJ, a range of 10 km, telescope diameter of 40.6 cm (16 in.), and a system bandwidth and digitization rate of 100 MHz. The value of β at which signal equals noise is 10^{-9} m^{-1}. This is on the extreme low end of the range of backscatter values found in the troposphere at 1 μm. Of course, actual system performance will not be this high, as collection inefficiencies and turbulent effects will lessen the signal. If the pulse length is 3 μsec, and the range gate is the same as the pulse length, the single-pulse velocity error is 0.33 m/sec for a 0.9-km depth resolution at a range of 10 km, when all error is due to noise.

A second example of interest is a satellite-based system with a 1-m diam receiving telescope at an 800-km altitude above the earth's surface. For a β value of 3×10^{-8} m^{-1} (molecular scatter = aerosol scatter) we find that the required pulse energy for SNR = 1 is 3 J.

V. Neodymium-based Coherent lidar

Pulsed reference-beam coherent lidar systems put two principal requirements on the laser technology: first, the low-power oscillator must be stabilized so that the frequency drift during the pulse round trip time contributes only a small fraction of the allowable frequency error; second, a high-energy pulse must be transmitted at a known offset frequency from the oscillator to well within the allowable frequency error. A system operating at 1 μm with a velocity error of 0.5 m/sec must have a frequency stability well under 1 MHz. For a range of 15 km, the required duration of this stability is 100 μsec.

The necessary frequency stability has been demonstrated in Nd:YAG at low powers.[13,14] Frequency shifting the 1-μm wavelength is easily done by acoustooptic or electrooptic modulation. The Nd:YAG laser offers the additional advantage of extremely high-gain amplification due to the high-energy storage density possible in solid-state lasers. Systems with gains as high as 54 dB have been built.[15] The master oscillator power amplifier (MOPA) configuration for a laser transmitter is ideally suited for the intrinsically high-gain Nd:YAG laser. Frequency chirp during amplification is extremely low.

A system operating from a satellite will see a large Doppler shift due to the motion of the satellite. For example, at a 7.7-km/sec ground velocity with an angle of observation 10° from vertical, the frequency offset is 2.5 GHz. Nd:YAG can be easily tuned over a 30-GHz wide range. We have demonstrated a small Nd:YAG oscillator pumped by a semiconductor diode laser with a tuning range of 16 GHz. The entire oscillator and its pump laser weigh a fraction of a kilogram.

Radiation at 1.06 μm can be amplified to large energies at high repetition rates. Pulse energies of 1 J are available from Nd:YAG systems at repetition rates of 25 Hz with rod geometry lasers. Repetition rates up to 100 Hz appear feasible with zigzag slab geometry lasers.[15] Higher pulse energies at repetition rates up to a few hertz are available using Nd:glass amplifiers in the slab configuration. A pulse energy of 5 J at 2-μm duration and a repetition rate of 1 Hz have been produced by a combination Nd:YAG–Nd:glass system for use in combustion research.[15]

The operating efficiency of conventional Nd lasers is lower than the efficiency of CO_2 lasers. Pulsed YAG lasers operate at ~1% electrical-to-optical efficiency, while CO_2 lasers operate at ~5% efficiency. The inefficiency of neodymium systems is due to the low absorption of the flashlamp light by the Nd ions. Lasers optically pumped by narrowband light can be extremely efficient. Semiconductor diode lasers made from gallium aluminum arsenide emit at the wavelength of 0.81 μm, which is efficiently absorbed by the Nd ion. The overall efficiency of diode-pumped Nd:YAG is near 10%. Large arrays of diode lasers will be needed for pulsed pumping, and it is not yet clear that energies >1 J will be possible. Although diode arrays will certainly be costly, the very low voltage requirement (2 V), high efficiency, and inherent reliability of an all-solid-state design would be ideal for satellite use.

VI. Stanford Nd:YAG Remote Wind Sending lidar

We have initiated construction of a coherent lidar system using Nd:YAG. Although current technology is adequate, we are trying to increase the efficiency, compactness, and simplicity of the system by developing a single-crystal diode-pumped oscillator and a very high-gain multipass amplifier. Other components of the system will be conventional.

Figure 2 is a schematic of the system. A diode laser pumps a Nd:YAG crystal oscillator to which coatings are applied directly. The crystal is conduction cooled.

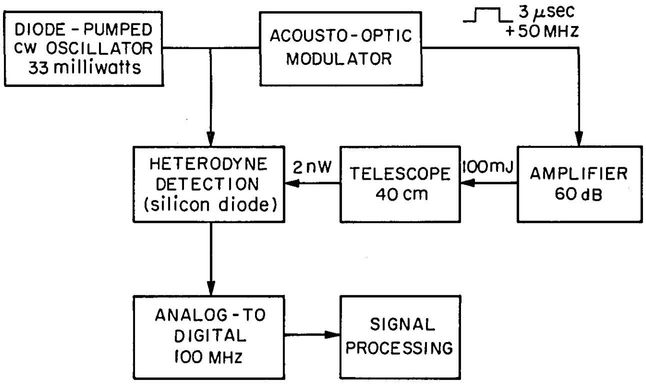

Fig. 2. Schematic of coherent lidar system under construction at Stanford. The diode-pumped single-crystal laser oscillator achieves excellent frequency stability (200 kHz in 0.1 sec) without active stabilization. The amplifier makes use of a single slab which is multipassed to achieve high gain efficiently. Other components are conventional.

In conventional laser oscillators, water cooling and mirror motion are major sources of frequency instability. We expect very good frequency stability without the necessity of feedback stabilization in this miniature diode-pumped crystal oscillator. Preliminary measurements of the beat frequency width between two independent oscillators yielded 200 kHz over a 0.1-sec integration time.

Most of the oscillator output is directed to the multipass amplifier. A zigzag slab of Nd:YAG[16] is used as the amplifier. The slab offers very low thermal distortion, high gain per pass due to the longer zigzag path. and the ability to pass several beams through the same volume of Nd:YAG and easily separate the beams outside the crystal.

An acoustooptic modulator is used to chop the amplified beam into pulses of a few microseconds duration. The modulator also creates a 50-MHz frequency offset to provide for Doppler detection at the intermediate frequency. Following pulse shaping by the acoustooptic modulator, the pulses are further amplified by a final saturated Nd:YAG amplifier.

The pulses are transmitted by a 40-cm diam telescope. The return signal is to be collected by the same telescope, mixed with a small fraction of the power from the local oscillator, and detected by a silicon photodiode. The signal is digitized at a rate of 100 MHz and analyzed conventionally.

We expect usable signal return (SNR > 1) at ranges up to 10 km, for a vertical beam path.

VII. Conclusion

A Nd:YAG-based coherent Doppler remote wind sensing system could be built using existing technology. A 1-μm system results in a smaller expected velocity error than a 10-μm system at the same level of SNR. The reduction in error is by a factor of between $\sqrt{10}$ and 10. The range resolution improves by a factor of 10 if the velocity error is held constant. A system operating at 1 μm can operate at a SNR at least 3$\times$ smaller than that of a 10-μm system and achieve the same velocity resolution.

The return signal from the atmosphere at the 1.06-μm wavelength of Nd:YAG will be 40–200$\times$ stronger than the return at the 10.6-μm CO_2 wavelength. The quantum-limited noise will be 100$\times$ higher at the Nd wavelength than at the CO_2 wavelength. Thus the SNR will be about the same.

The problems of signal reduction due to turbulence and near-field attenuation are greater at 1 μm. Systems with a small aperture and systems looking down from above the atmosphere will be troubled by these problems to only a small extent. Our large-aperture single-detector ground-based system will suffer signal reduction under turbulent conditions. We plan to study the severity of this effect.

The technologies of both carbon dioxide lasers and Nd lasers are well developed. Carbon dioxide lasers are more efficient than conventional flashlamp-pumped Nd lasers. Neodymium lasers are physically smaller. The developing technology of laser-diode-pumped Nd:YAG may improve Nd:YAG efficiency to the same level as CO_2 lasers. Although such lasers will be expensive, they may prove advantageous for satellite-based coherent lidar systems.

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References

1. P. S. Ray, R. J. Doviak, G. B. Walker, D. Sirmans, J. Carter, and B. Bumgarner, J. Appl. Meteorol. **14**, 1521 (1975).
2. R. J. Doviak and C. T. Jobson, J. Geophys. Res. **84**, 697 (1979).
3. M. J. Post, R. A. Richter, R. M. Hardesty, T. R. Lawrence, and F. F. Hall, Proc. Soc. Photo-Opt. Instrum. Eng. **300**, 60 (1981).
4. R. M. Huffaker, Ed., "Feasibility Study of Satellite-Borne Lidar Global Wind Monitoring System," NOAA Tech. Mem. ERL WPL-37 (1978).
5. D. S. Zrnic, IEEE Trans. Geosci. Electron. **GE-17**, 113 (1979).
6. R. V. Hess, P. Brockman, C. H. Bair, L. D. Staton, C. D. Lytle, L. M. Laughman, and M. L. Kaplan, Proc. Soc. Photo-Opt. Instrum. Eng. **415**, 52 (1983).
7. G. S. Kent, Institute for Atmospheric Optics & Remote Sensing, Hampton, Va.; personal communication.
8. G. S. Kent, G. K. Yue, U. O. Farrukh, and A. Deepak, Appl. Opt. **22**, 1655 (1983).
9. M. P. McCormick, P. Hamill, T. J. Pepin, W. P. Chu, T. J. Swissler, and L. R. McMaster, Bull. Am. Meteorol. Soc. **60**, 1038 (1979).
10. P. B. Russell, B. M. Morley, J. M. Livingston, G. W. Grams, and E. M. Patterson, Appl. Opt. **21**, 1541 (1982).
11. S. F. Clifford and L. Lading, Appl. Opt. **22**, 1696 (1983).
12. S. F. Clifford and S. M. Wandzura, Appl. Opt. **20**, 514 (1981).
13. H. G. Danielmeyer, "Progress in Nd:YAG lasers," in *Lasers, Vol. 4*, A. K. Levine and A. J. DeMaria, Eds. (Marcel Dekker, New York, 1976).
14. Y. L. Sun and R. L. Byer, Opt. Lett. **7**, 408 (1982).
15. P. J. Brannon, F. R. Franklin, and E. D. Jones, Appl. Opt. **21**, 1758 (1982).
16. T. J. Kane, R. C. Eckardt, and R. L. Byer, IEEE J. Quantum Electron. **QE-19**, 1351 (1983).