1995

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

OPTICAL AMPLIFIERS FOR COHERENT LIDAR

Prepared by: Richard Fork, Ph.D.

Academic Rank: Professor
                                      Electrical & Computer Engineering

Institution and Department: University of Alabama in Huntsville
                                      Electrical & Computer Engineering

NASA/MSFC:

    Laboratory: Astrionics

MSFC Colleague: Michael J. Kavaya, Ph.D.

Optical Amplifiers for Coherent Lidar

R.L. Fork and A. Ghobrial
University of Alabama in Huntsville
Huntsville, AL 35899

Abstract

We examine application of optical amplification to coherent lidar for the case of a weak return signal (a number of quanta of the return optical field close to unity). We consider the option that has been explored to date, namely, incorporation of an optical amplifier operated in a linear manner located after reception of the signal and immediately prior to heterodyning and photodetection. We also consider alternative strategies where the coherent interaction, the nonlinear processes, and the amplification are not necessarily constrained to occur in the manner investigated to date. We include the complications that occur because of mechanisms that occur a the level of a few, or one, quantum excitation. Two factors combine in the work to date that limit the value of the approach. These are: (a) the weak signal tends to require operation of the amplifier in the linear regime where the important advantages of nonlinear optical processing are not accessed , (b) the linear optical amplifier has a -3dB noise figure (SN_{out}/SN_{in}) that necessarily degrades the signal. Some improvement is gained because the gain provided by the optical amplifier can be used to overcome losses in the heterodyned process and photodetection. The result, however, is that introduction of an optical amplifier in a well optimized coherent lidar system results in, at best, a modest improvement in signal to noise. Some improvement may also be realized on incorporating more optical components in a coherent lidar system for purely practical reasons. For example, more compact, lighter weight, components, more robust alignment, or more rapid processing may be gained. We further find that there remain a number of potentially valuable, but unexplored options offered both by the rapidly expanding base of optical technology and the recent investigation of novel nonlinear coherent interference phenomena occurring at the single quantum excitation level. Key findings are: (1) insertion of linear optical amplifiers in well optimized conventional lidar systems offers modest improvements, at best , (2) the practical advantages of optical amplifiers, especially fiber amplifiers, such as ease of alignment, compactness, efficiency, lightweight, etc., warrant further investigation for coherent lidar, (3) the possibility of more fully optical lidar systems should be explored, (4) advantages gained by use of coherent interference of optical fields at the level of one, or a few, signal quanta should be explored, (5) amplification without inversion, population trapping, and use of electromagnetic induced transparency warrant investigation in connection with coherent lidar, (6) these new findings are probably more applicable to earth related NASA work, although applications to deep space should not be excluded, and (7) our own work in the Ultrafast Laboratory at UAH along some of the above lines of investigation, may be useful.

1. Introduction

Both ground based and airborne laser radar systems are being explored and developed for wind velocity measurements. The measurements provided by these systems yield essential information needed, e.g., for space shuttle launches and aircraft flights. Timeliness of the information may have life and death consequences. A real time global wind profile; however, remains a challenge beyond the reach of current technology.

We focus here on strategies that need to be addressed if a goal, such as real time global wind profiling, is to be realized. In particular we examine the problem of optimizing the acquisition of information under circumstances where quantum properties, coherent interference, and nonlinear interactions of the signal, reference fields, and the transmission medium may be important. Space based technology tends to require maximally efficient performance and it is reasonable to expect that space based wind sensing will be no exception.

Addition of an optical amplifier to a coherent lidar system deserves exploration. Optical amplifiers have had a powerful and positive impact on emerging optical information transmission and handling systems. A fundamental problem is encountered, however, in the manner used to date in applying optical amplifiers to coherent lidar. Optical amplifiers are traditionally most effective if used in conjunction with nonlinear processes before a signal has been reduced to the level of a few quanta. By using an optical amplifier after reception and immediately prior to detection we limit our options. In particular, optical amplifiers used at the level of a few quanta tend to introduce spontaneous emission noise in ways that are difficult to avoid. On the other hand the nature of lidar applications makes it difficult to introduce the optical amplifier at any other point in the system.

In essence we consider two approaches: (1) conventional, where the optical amplifier is introduced into an existing coherent lidar system where a return signal of a few quanta is to be amplified immediately prior to photodetection, and (2) non conventional, where we allow more novel and more distributed use of amplification, coherent interference, and nonlinear optical processes including excitation levels of one or a few quanta. In the former case we find some practical advantages, but little opportunity for revolutionary progress. In the latter case we find no immediate practical advantages, but do find a potential for more revolutionary progress in coherent lidar. These non-conventional strategies, interestingly, make contact with vigorous and rapidly emerging new fields and new technology.

1.1 Signal to noise considerations

Conventional coherent lidar already uses optical interactions in a powerful and effective manner. The signal, heterodyned against a local optical oscillator is, in essence, noiselessly amplified. For an ideal system coherent detection provides a 3dB advantage over direct detection. The frequency shift of the return signal is also made easily detectable since the heterodyne process modulates the resulting photocurrent at the difference frequency between the initial and return signals. Linear optical amplifiers, on the other hand, introduce a 3 dB noise penalty. In addition access to optimum performance of the linear optical amplifier can be expected to require spectral filtering and temporal gating of the return signal to avoid further unnecessary degradation of signal to noise arising from excess spontaneous emission.

The most obvious advantage of the linear optical amplifier used for a weak return signal is that of overcoming the losses that occur between the output of the amplifier and the conversion of the photons in the return signal to electrical current in the photodetector.

Typical sources of such losses are quantum and heterodyne efficiencies less than unity, and any other losses that occur after exit of the signal from the optical amplifier and before conversion to photoelectrons. In general, we see the principal value of the optical amplifier as used in experimental work to date as compensating these losses at the receiver.

1.2 Optical signal processing issues other than signal to noise considerations

Aside from issues of signal to noise performance emerging optical technology may offer improvements to state of the art coherent lidar systems. Diode pumped optical fiber amplifiers offer advances in compact, robust, efficient, lightweight easily aligned technology. Cladding pumped amplifiers offer very high average power while maintaining highly coherent wavefronts. Fiber amplifiers can also assist in achieving and maintaining robust alignment of wavefronts. More fully optical coherent lidar systems may eventually offer more rapid processing. Recent advances in fiber grating techniques may provide a means for spectrally resolving a return signal with sufficient resolution and efficiency to allow frequency shift resolution for wind sensing that is more fully optical. Other advantages not yet perceived may emerge since this field is still evolving in substantial ways.

1.3 Novel strategies

In general, we find a proliferation of new optical technology and substantial new work and ideas regarding coherent nonlinear interactions where quantum phenomena can be important. While we cannot guarantee substantial benefit to coherent lidar, the richness of the technology and the vigorous new experimental and theoretical work appear to warrant a "back to the drawing board" examination of coherent lidar and systems that perform functions similar to coherent lidar. In essence we note the physical mechanisms that make coherent lidar effective are coherent interaction and nonlinear mixing that operate in a useful manner at excitation levels of one, or a few, quanta of the radiation field. Novel combinations of these mechanisms may work to advantage.

If we relax the condition that improvement be sought only by inserting a linear optical amplifier at the receiver of a conventional coherent lidar more options emerge. One direction of interest appears to be that of using interference of quantum states at low where nonlinear processes also have significant consequence. New physical phenomena occur and new options are accessed. Electromagnetically induced transparency (EIT) [1],[2] and optical amplification without inversion [3] are two recent areas of vigorous research that warrant investigation. Our own work in this area may be of significance.[18]

2. Conventional and non-conventional approaches

There are essentially two paths that can be followed, one relatively conventional and the other non-conventional. We explore both options. The conventional path appears to offer modest, but readily implemented improvements. The non-conventional path appears to offer more possibilities for revolutionary advances, but with a correspondingly lower probability of near term working systems. Both paths appear to warrant consideration.

2.1 Introduction of optical amplifiers into conventional lidar systems

As regards background on existing coherent lidar there are a number of good recent publications that examine topics of current interest and provide references to earlier work.. Frehlich [4], [5] and Kavaya [5] have investigated the signal to noise and heterodyne efficiency of coherent heterodyne laser radar under the Fresnel approximation and general

conditions. This includes spatially random fields, refractive turbulence, monostatic and bistatic configuration, detector geometry and targets. Frehlich has compared the performance of 2 and 10 micron coherent lidar systems [6]. Hawley et al [7] investigate the performance of the coherent launch-site atmospheric wind sounder (CLAWS), a Nd:YAG based coherent lidar operating at 1.06 micron with 1-J energy per pulse. Salisbury [8],[9] has performed a combined calculational and experimental test of a system that incorporates a neodymium doped fiber preamplifier, and Baker et al [10] have written a general analysis of the lidar measurement of winds from space with an emphasis on the CO_2 laser at 10 microns originally proposed for the Laser Atmospheric Wind Sounder (LAWS).

Experimentally oriented studies, such as those of Salisbury[9], Rahm [11] and Morley [16] find improvement on introducing optical amplifiers to existing coherent lidar systems; however, their findings do not appear to be in contradiction to the above interpretation of the improvement. In general, the basic conclusion seems to be that, a system that departs significantly from ideal performance can be correspondingly improved by adding an optical amplifier; however, a well designed coherent lidar can at best experience modest improvements. Other important practical benefits, such as those gained by: alignment of wave fronts, robust alignment of pump and probe, and light weight, compact character of components are discussed to a limited extent.

The general problem of signal to noise in coherent heterodyne and direct detection systems has been analyzed by a number of authors e.g., Agrawal [12]. Theoretical analyses of optical amplifiers, Caves [13], Bondurant [14] assign a noise figure of -3 dB to optical amplifiers for incoherent signals and -6 dB to optical amplifiers for coherent signals. There also appears to be general agreement that improvement by the product of the reciprocal of the heterodyne efficiency and the quantum efficiency can be argued for in a fundamental manner [12],[8]. In essence photons that are lost in the detection process before excitation of a photoelectron occurs cause a degradation in the signal to noise. This degradation of signal can be avoided by introduction of an amplifier that is located at the receiver, but positioned before the photodetection and heterodyne mixing, but at the price of introducing spontaneous emission noise.

The conclusions concerning conventional use of optical amplifiers for coherent lidar are: (1) the heterodyne step in coherent lidar is a powerful technique for sensing return signals containing a few quanta, (2) the possibility of some modest improvement in signal to noise may be realized on introduction of an optical amplifier (3) This improvement is attributable to compensation for losses occurring after amplification and prior to detection. (4) without some substantial change in strategy this approach is unlikely to cause revolutionary improvements in a well designed existing coherent lidar, (5) practical advantages such as, more robust alignment, more efficient pumping, better wavefront quality, more compact technology, lighter weight, and opportunities for more fully optical and faster signal processing may be realized, aside from signal to noise considerations.

2.2 Non-conventional strategies

The non-conventional strategies do not appear to be easily addressed; however, attention appears warranted. We approach the task by dividing the discussion into four parts: (1) Novel preparation and transmission of the emitted signal, (2) novel amplification and processing of the return signal, (3) novel detection and (4) novel interactive generation-transmission-reception strategies.

2.2.1 Novel preparation and transmission of the emitted signal: There is new science and technology of electromagnetically induced transparency (EIT) that is vigorous

medium can result in a nonlinearly induced transparency. The applications to NASA would tend to be found where the lidar signal propagates through media that would normally be lossy or distorting. Reduced diffraction and hence enhanced signal may be found under some circumstances. The physical phenomena is not trivial, but results from interference effects at the single quantum excitation level that can drastically alter the propagation of an electromagnetic field through otherwise lossy and distorting media. The current experimental work relates primarily to laboratory efforts, e.g., metal vapors in a highly controlled environment, or, in our work, to cooled solid state samples. Legitimate questions can be raised as to whether this technology will ever be of practical interest to NASA. On the other hand, the progress in laboratory demonstration and in theoretical mastery of this interesting phenomena are impressive. Possible breakthroughs may occur in high signal rate optical communications technology or in sensing between space and ground through otherwise obscuring media. There is also separate work on diffractionless beams that might be followed, but in the opinion of the PI this latter work does not appear promising [17].

2.2.2 Novel amplification and processing of the return signal

There is an active field addressing techniques for reducing quantum noise in amplifiers. These techniques usually offer an improvement by decreasing noise in a given quadrature and increasing noise in an (unused) conjugate quadrature. We have not seen an obvious strategy of clear value to NASA, but we similarly do not see cause to rule out strategies of this kind.

An approach that might be of some interest would be that of spectrally resolving the signal return prior to detection in a manner that does not discard any signal prematurely. This might be done, for example, using emerging fiber grating array technology. Fiber grating arrays provide high spectral resolution, high efficiency, compact and lightweight components, rugged alignment, and contact with rapidly developing, relatively low cost, communication technology.

We note also the recent successful operation of synthetic aperture optical detection. While this technique is currently only used for ground based observation of satellites it represents a novel technology. This approach appears more useful for enhancing spatial resolution than for improving signal gathering efficiency, but warrants attention.

2.2.3 Novel Detection techniques

Noiseless amplification is not limited to heterodyne strategies. Bondurant, e.g., describes a system where the noise figure of an amplifier is reduced to zero [11]. There, intense beams in a Mach-Zehnder interferometer are designed to balance in such a way that a weak signal in an on-off keying arrangement can be amplified, in principle, with no increase in noise. This example has not been proven experimentally, but it helps make the case that noiseless amplification at the level of a few signal quanta may be a more general phenomena than previously thought. Other schemes for noise figure improvement have been discussed and some improvement demonstrated, as in nonlinear fiber loops. Here squeezing is used to reduce the noise in a particular quadrature.

In our own work we see evidence of nonlinear processes playing a role at the level of single quantum excitations. The main point here is that there appears to be considerable reason to expect improvements in signal detection near the single quantum level by using coherent interference and nonlinear processes. An approach of this kind could provide significant gains and should not be ruled out. At the same time these techniques should not be relied on in the short term since they are demanding of realization, and application to a

problem of practical interest to NASA could be long in maturing. Applications in the atmosphere are more demanding than current laboratory experiments. The fluctuations of the atmosphere and the long distances used in lidar may render the electromagnetic induced transparency techniques that work in a laboratory setting ineffective for lidar. On the other hand, very substantial DoD funding is directed at this set of problems and a prime motivation for that funding is the possibility of enhanced transmission through the atmosphere.

A third relatively unconventional theme is that of a more fully optical lidar system. The incoming signal might be frequency resolved using fiber gratings prior to amplification and a spectrally selective, temporally gated, and nonlinear optical amplifier used in place of current rf and microwave technology. This approach could, in principle, provide faster processing and could be as good or better as regards signal to noise ratio. This is an area where the path is not obvious, but research effort could be warranted.

2.2.4 Interactive generation, transmission and detection

A last area is that of interactive generation, transmission and detection that includes coherent interference, single quantum phenomena, nonlinear processes, and amplification in a relatively distributed interactive manner over the entire signal path. Because light propagates rapidly, there is an opportunity to use optical means to sense the optical path and then modify the generated signal, and possibly the detection scheme, so as to optimize the sensing process in more holistic manner. Electromagnetic induced transparency has shown some advantages in this regard. A control signal sent along with a second signal has demonstrated that otherwise distorting and lossy mechanisms can be significantly reduced. This is a complex, but active and promising area. Our best guess is that improvements that can be adapted to NASA applications are unlikely in the immediate future; however, close attention to this field is warranted.

3. Conclusions

Our essential conclusions are: (1) incorporation of an optical amplifier in existing lidar systems as a preamplifier for weak return signals offers some modest improvements, but is unlikely to result in major breakthroughs, (2) recent work that predicts, and in some cases finds, modest improvement for coherent lidar through application of optical amplifiers appears substantially correct, but the improvement tends to arise from overcoming flaws in the existing technology rather than from a fundamental advantage, (3) if the roles of optical amplification, coherent interference, nonlinear signal processing, use of novel optical technology, are viewed broadly, interesting opportunities emerge, (4) this latter work is at a relatively early stage of development and is probably best viewed as an area of basic research to be pursued and monitored, rather than exploited in the short term.(5) Our own work on electromagnetically induced transparency at the level of one, or a few quanta bears some relevance and warrants following.

References

[1] "Normal modes for electromagnetically induced transparency", S.E. Harris, Physical Review Letters 72 (January 1994) pp 52-5.

[2] "Preparation energy for electromagnetically induced transparency", S.E. Harris and Zhen-Fei Lou, Physical Review A **52** (August 1995) pp R928-31

[3] " Degenerate Quantum-Beat Laser: Lasing without inversion and inversion without lasing", Marlan O. Scully, Physical Review Letters **62** (June 1989) pp 2813-6

[4] "Heterodyne efficiency for a coherent laser radar with diffuse or aerosol targets," R.G. Frehlich, Journal of Modern Optics **41** (No. 11), 2115-2129.

[5] "Coherent laser radar performance for general atmospheric refractive turbulence," R.G. Frehlich and M.J. Kavaya, Applied Optics **30** (December 1991) pp 5325-52.

[6] "Comparison of 2- and 10um coherent Doppler lidar performance," R. Frehlich, Journal of Atmospheric and Oceanic Technology, **12** (April 1995) pp 415-20.

[7] "Coherent launch-side atmospheric wind sounder: theory and experiment," J. G. Hawley, R. Targ, S. W. Henderson, C. P. Hale, M. J. Kavaya, D. Moerder, Applied Optics **32** (August 1993) pp 4557-68.

[8] "Sensitivity improvement of a 1-um ladar system incorporating an optical fiber preamplifier," M. S. Salisbury, P. F. McManamon, B. D. Duncan, Optical Engineering **32** (November 1993) pp 2671-80.

[9] "Optical-fiber preamplifiers for ladar detection and associated measurements for improving the signal-to-noise ratio," M. S. Salisbury, P. F. McManamon, B. D. Duncan, Optical Engineering 33 (December 1994) pp 4023-32.

[10] "Lidar-measured winds from space: A key component for weather and climate prediction," W.E. Baker, et al, Bulletin of the American Meteorological Society **76** (June 1995) pp 869-88.

[11] "Performance of an optical detector preamplifier," S. Rahm, Optics Letters **18** (September 1993) pp 1559-60.

[12] "Fiber-Optic Communication Systems", Govind P. Agrawal, Wiley series in microwave and optical engineering, 1992

[13] "Quantum limits on noise in linear amplifiers," C.M. Caves, Physical Review D, **26** (October 1982) pp 1817-39.

[14] "Quantum noise properties of a nonlinear amplifier," R.S. Bondurant, Physical Review Letters **71** (September 1993) pp 1709-1710.

[15] "Recent advances in high power semiconductor laser diodes", David F. Welch (tutorial) OSA annual meeting (September 1995)

[16] " Enhancement of coherent laser radar performance by predetection amplification ", R.J. Morley, H.J. Baker, D.R. Hall, M. Harris, and J.M. Vaughan

[17] " Localized transmission of electromagnetic energy ", R. W. Ziolkowski Physical Review A **39** (February 1989) pp2005-33.

[18] Manuscript in preparation.

Background References: I. Detection:

"Noise in homodyne and heterodyne detection," H.P. Yuen, V.W.S. Chan, Optics Letters **8** (March 1983), pp 177-9.

"Sensitivity enhancement using coherent heterodyne detection," G. Lachs, S.M. Zaidi, A.K. Singh, Journal of Lightwave Technology **12** (June 1994) pp 1036-41.

"Quantum noise and excess noise in optical homodyne and heterodyne receivers," J.H. Shapiro, MIT, report under NRL contract N0014-81-K-0662.

"Performance of a 2um coherent Doppler lidar for wind measurements," R. Frehlich, S.M. Hannon, S. W. Henderson, Journal of Atmosphere and Oceanic Technology, **11** (December 1994) pp 1517-1528.

"Optimal local oscillator field for a monostatic coherent laser radar with a circular aperture," R. Frehlich, Applied Optics **32** (August 1993) pp 4569-4577.

"Speckle characteristics of atmospherically backscattered laser light," J.H. Churnside, H.T. Yura, Applied Optics **22** (September 1983) pp 2559-2565.

"Performance of Mean-frequency estimators for Doppler radar and lidar," R.G. Frehlich and M.J. Yadlowsky, Journal of Atmospheric and Oceanic Technology **11** (October 1994) pp 1217-20.

"Coherent versus incoherent ladar detection at 2.09 um," J.A. Overbeck, M.B. Mark, S.H. McCracken, P.F. McManamon, B.D. Duncan, Optical Engineering **32** (November 1993) pp 2681-9.

"Cramer-Rao bound for Gaussian random processes and applications to radar processing of atmospheric signals," R. Frehlich, IEEE Transactions on Geoscience and Remote Sensing **31** (November 1993) pp 1123-31.

"Doppler lidar atmospheric wind sensors: a comparative performance evaluation for global measurement applications from earth orbit," R.T. Menzies, Applied Optics **25** (August 1986) pp 2546-2553.

II. Optical Amplifiers

"Laser-amplifier gain an noise", R.Loudon and Harris, Physical Review A **48**, (July 1993) pp 681-701

"Optical Amplification: Current Status and Future Trends," M. Federighi and F. Di Pasquale, SPIE **2450** (March 1995) pp 110-120.

"Measuring and modifying the spontaneous emission rate of erbium near an interface," E. Snoeks, A. Lagendijk, A. Polman, Physical Review Letters **74** (March 1995) pp 2459-62.

"Efficient erbium-doped fiber amplifiers incorporating an optical isolator," M.N. Zervas, R.I. Laming, D.N. Payne, IEEE JQE, **31** (March 1995) pp 472-80.

"Performance evaluation of EDFA preamplified receivers taking into account intersymbol interference," L. F.B. Ribeiro, J. R.F. Da Rocha, J. L. Pinto, Journal of Lightwave Technology **13** (February 1995) pp 225-31.

"Quantum Noise Reduction in Optical Amplification," Z.Y. Ou, S.F. Pereira, H.J. Kimble, Physical Review Letters, **70** (May 1993) pp 3239-3242.

"High-sensitivity two-stage erbium-doped fiber preamplifier at 10 Gb/s," R.I. Laming, A.H. Gnauck, C.R. Giles, M.N. Zervas, D.N. Payne, IEEE Photonics Technology Letter **4** (December 1992) pp 1348-50.

"Quantum nondemolition measurement of the photon number via the optical Kerr effect," N. Imoto, H.A. Haus, Y. Yamamoto, Physical Review A **32** (October 1985) pp 2287-92.

"Near-quantum optimum receivers for the phase-quadrature coherent-state channel," R.S. Bondurant, Optics Letters **18** (November 1993) pp 1896-8.

""Laser detector preamplifier for CO2 lasers," promotional literature provided August 1987 by Pulse Systems, Inc., of Los Alamos, N.M. to attendees of Aspen Coherent Laser Radar Conference.

III. Actual detection systems/experiments

"Considerations and calculations concerning the application of an optical amplifier as an output amplifier and preamplifier," F. Malota, European Space Agency translation ESA-TT-I004 (September 1986).

"Pre-detection amplification using a multifold CO2 laser gain cell," R.J. Morley, D.R. Hall, H.J. Baker, Proceedings of the 7th Conference on Coherent Laser Radar Applications and Technology, FA6 (July 19-23, 1993).

"Optical fiber preamplifiers for ladar detection and associated signal to noise ratio improvement measurements," M.S. Salisbury, P. F. McManamon, B. D. Duncan, unpublished manuscript, Feb. 7, 1994.

"Discrete spectral peak estimation in incoherent backscatter heterodyne lidar. I: Spectral accumulation and the Cramer-Rao lower bound," B.J. Rye, R. M. Hardesty, IEEE Transactions on Geoscience and Remote Sensing, **31** (January 1993) pp 16-27.

"Doppler lidar atmospheric wind sensor: reevaluation of a 355-nm incoherent Doppler lidar," D. Rees and I.S. McDermid, Applied Optics **29** (October 1990) pp 4133-44.

"Sensitivity and signal to noise ratio improvement of a one micron ladar system incorporating a neodymium doped optical fiber preamplifier," M. S. Salisbury, Electro-optics Techniques Section, Wright-Patterson AFB, Ohio; final report for period August 1991 to November 1993.

"Analysis of measurements for solid state laser remote lidar system," F. Amzajerdian, Center for Applied Optics, University of Alabama in Huntsville, submitted to NASA/MSFC, contract no. NAS8-38609, June 1, 1993-September 31, 1994.

"Improvement of a CO2 Doppler lidar with an optical detector preamplifier," S. Rahm, C. Loth, FA5, 7th Conference on Coherent Laser Radar Applications and Technology, July 19-23, 1993.

"Lidar aerosol backscatter measurements: systematic modeling and calibration error considerations," M. J. Kavaya, R. T. Menzies, Applied Optics **24** (November 1985) pp 3444-53.