Communication Sciences and Engineering

19. Optical Propagation and Communication

Academic Research Staff

Prof. R.S. Kennedy, Prof. R.H. Rediker, Prof. J.H. Shapiro, Prof. C. Warde

Graduate Students

P.L. Bogler, R.S. Bondurant, J.J. Fratamico, F. Hakimi, S.T. Lau, J. Nakai, T.T. Nguyen, D.M. Papurt, J.J. Prisco, R.P. Schloss, S.S. Wagner

The central theme of our programs has been to advance the understanding of optical and quasi-optical communication and radar systems. Broadly speaking, this has entailed: developing system-analytic models for important optical channels; using these models to derive the fundamental limits on system performance; and identifying, and establishing the feasibility of, techniques and devices which can be used to approach these performance limits.

19.1 Improved Low-Visibility Optical Communication

National Science Foundation (Grant ENG78-21603)

Jeffrey H. Shapiro, Robert S. Kennedy, Cardinal Warde, Jun Nakai, Trung T. Nguyen

As the lower frequency portions of the electromagnetic spectrum become more congested, atmospheric optical communication systems appear to be a natural choice for short-haul terrestrial transmission when cable rights-of-way are unobtainable, or frequent link and network reconfiguration is necessary. Such systems will experience occasional outages due to local adverse weather conditions, and the frequency and duration of these outages will, in turn, be a major determinant of the extent to which atmospheric optical systems are used. In this program, which is carried out jointly with MIT's Center for Material Science and Engineering (CMSE), we have been conducting an investigation to: determine this outage time; determine the degree to which it can be reduced by appropriate system design; and develop the devices needed to achieve this reduction in practice.

The potential for reducing the outage time resides in the energy and information contained in the scattered component of the received field. A conventional narrow field-of-view optical receiver used in a low-visibility atmospheric environment responds only to the extinguished direct beam arriving along the boresight from the transmitter. Yet, at most visible and at many infrared wavelengths extinction in bad weather is due primarily to scattering rather than absorption. To reap the potential communication benefits of scattered-light utilization requires a simultaneous attack on issues of optical wave propagation, communication system design, and device technology. We have addressed components of all of these issues, the latter through the CMSE participation. A summary of our recent achievements, and some plans for future research follow.

a. Low-Visibility Propagation[1]

Laser and incoherent-source propagation measurements that we have made over a variety of line-of-sight paths in low-visibility weather have shown only modest amounts of angular spreading and essentially no multipath for optical thicknesses less than 10. Moreover, power transmission vs. range seems to be an exponential function whose decay rate decreases with increasing receiver field of view.

Based on the preceding experimental evidence, we have developed a multiple- forward-scatter (MFS) propagation theory. The MFS approach is well-suited to providing the channel-parameter values needed for communication system design. The power transfer and angular spread predictions of this model are reasonably grounded in experiment, but the extent of the region of applicability of MFS theory is still incompletely understood. However, the overall quality of the MFS model is such that propagation experiments and modeling *per se* have ceased being major components of this program.

b. Communication Theory[2]

The communication theory of single-bit transmission through the low- visibility channel is fairly complete. In particular, by combining the MFS propagation model with low-photon coherence (LPC) optical detection theory, we have established a procedure for preliminary assessment of link operability given the link geometry and the atmospheric scattering parameters. During the past year, some experimental corroboration of the tradeoffs between narrow field-of-view and wide field-of-view reception was obtained by using our 20 pulse per second propagation-measurement equipment to stimulate a pulse-position modulated (PPM) communication link.[3] In a recently completed doctoral dissertation,[4] Nakai has treated the performance of coded optical communication systems. His analysis shows that a significant operating-range extension may be possible through a combination of large-alphabet PPM signaling with an error-correcting code.

c. Future Directions

Our work to date on this program has borne the following fruit. Low-visibility atmospheric optical communication links can now be analyzed with some confidence. By exploiting scattered light, useful link operation can be maintained beyond the limit set by extinction of the direct beam. Technology development can help extend scattered-light operating range, but true all-weather capability at high data rates over kilometer or longer paths cannot be guaranteed. Our depth of understanding of atmospheric optical communication decreases rapidly, however, as we pass from the single-link level to the communication system and communication network levels. It is our ignorance at these higher levels that, we believe, currently limits the commercial usage of atmospheric optical communications. As a result, we have made system and network issues the central focus of our future work in this program.

References

1. W.S. Ross, W.P. Jaeger, J. Nakai, T.T. Nguyen, and J.H. Shapiro, "Atmospheric Optical Propagation: An Integrated Approach," Opt. Engr. 21, 775-785 (1982).
2. J.H. Shapiro and C. Warde, "Optical Communication through Low-Visibility Weather," Opt. Engr. 20, 76-83 (1981).
3. J.C. Berets, "Error-Rates of a Pulse-Position-Modulated Atmospheric Optical Communication System," S.B. Thesis, Department of Electrical Engineering and Computer Science, M.I.T., May 1981.
4. J. Nakai, "Coding and Modulation Analysis for Optical Communication Channels," Ph.D. Thesis, Department of Electrical Engineering and Computer Science, M.I.T., January 1982.

19.2 Atmospheric Propagation Effects on Infrared Radars

U.S. Army Research Office - Durham (Contract DAAG29-80-K-0022)
Jeffrey H. Shapiro, David M. Papurt, Sun T. Lau

The development of laser technology offers new alternatives for the problems of target detection and imaging. In particular, compact coherent laser radars have the potential for greatly improved angle, range, and velocity resolution relative to their microwave-radar counterparts. The performance of the laser systems, however, may be severely restricted by the turbulence, absorption, and scattering encountered in optical beam propagation through the atmosphere; these effects are relatively benign for most microwave radars. In a precursor study, which was funded through the MIT Lincoln Laboratory[1,2] and later published in,[3] we developed statistical models for the effects of propagation through atmospheric turbulence on a compact coherent laser radar. Using these models, we showed, for realistic parameter values, that compact coherent laser radars should be immune to turbulence-induced beam spreading and coherence loss. Target speckle and atmospheric scintillation, however, were predicted to be key limiting factors on single-frame imaging and target-detection performance. This program is aimed at obtaining a quantitative understanding of these target-reflection and atmospheric-propagation effects on compact coherent laser radars through a combination of theory and experiments. Under a collaboration arrangement with the Optics Division of the MIT Lincoln Laboratory, the experimental portions of the research are being carried out on the compact CO_2-laser radar under development there.[4]

The primary goal of the experimental work has been verification of the saturation signal-to-noise ratios, and target-return probability models established in[1-3] for speckle and glint targets viewed through atmospheric turbulence. Initial clear-weather infrared radar measurements collected with simultaneous scintillation data over a 1-km path have been analyzed during the past year.[5] In very light turbulence, good agreement has been obtained between experimental return statistics off a flame-sprayed aluminum plate and the exponential laser-speckle distribution. Measurements off a retroreflector were not reconcilable with the statistics predicted for a scintillation-limited glint target. Because the radar data were obtained in a scanning (imaging) mode, it was hypothesized that scanner-reset error was the prime fluctuation mechanism in the retroreflector data. By developing a statistical model for this fluctuation mechanism, we have been able to verify our hypothesis, and obtain an experimental value for the scanner-reset accuracy. To probe the scintillation effect on a glint target, future data will be taken in the staring mode, i.e., with the scanner disabled.

The primary goal of the theoretical work has been the extension of our radar analysis to encompass the multiple-scattering effects present in bad weather conditions. Using the multiple-forward-scatter propagation model that was developed in our low-visibility optical communication work, we have been able to obtain saturation signal-to-noise ratios and target-detection performance results for coherent laser radar operation in bad weather.[5,6] However, because the extinction at the 10.6 μm CO_2 laser wavelength is due primarily to absorption rather than scattering, the use of scattered light to improve coherent laser radar weather penetration must await technology development at a wavelength which has near-unity albedo under the conditions of interest. Moreover, our analysis indicates that such scattered-light operation will be subject to greatly reduced spatial resolution and will suffer from drastically reduced carrier-to-noise ratio, as compared to clear-weather operation. Thus bad-weather radar use may be limited to coarse-resolution acquisition and imaging tasks. Further work is being done on these application issues.

References

1. J.H. Shapiro, "Imaging and Target Detection with a Heterodyne-Reception Optical Radar," Project Report TST-24, M.I.T. Lincoln Laboratory (Oct. 13, 1978).
2. B.A. Capron, J.H. Shapiro, and R.C. Harney, "Turbulence Effects on the Receiver Operating Characteristics of a Heterodyne-Reception Optical Radar," Project Report TST-33, M.I.T. Lincoln Laboratory (July 25, 1979).
3. J.H. Shapiro, B.A. Capron, and R.C. Harney, "Imaging and Target Detection with a Heterodyne-Reception Optical Radar," Appl. Opt. 20, 3292-3313 (1981).
4. R.C. Harney and R.J. Hull, "Compact Infrared Radar Technology," Proc. SPIE 227, 162-170 (1980).
5. D.M. Papurt, "Atmospheric Effects on Heterodyne-Reception Optical Radars," Ph.D. Thesis Proposal, Department of Electrical Engineering and Computer Science, M.I.T., September 1981.
6. D.M. Papurt, J.H. Shapiro, and R.C. Harney, "Atmospheric Propagation Effects on Coherent Laser Radars," Proc. SPIE 300, 86-99 (1981).

19.3 Improved Millimeter-Wave Communication Through Rain

U.S. Navy - Office of Naval Research (Contract N00014-81-K-0662)

Jeffrey H. Shapiro, John J. Fratamico, Philip L. Bogler

The increased path loss due to rain has long been recognized as a key factor limiting the extension of microwave satellite communications into the millimeter-wave spectral region. It turns out that the millimeter-wave albedo in rain may be on the order of 0.5. As a result, under severe rain conditions there may be significant amounts of multiply-scattered radiation present in the vicinity of the receiving antenna for a satellite downlink. Communication theory teaches that optimum processors will utilize all received radiation which bears a statistical dependence on the transmitted message. Thus, in this program we are considering receivers which exploit the multiply-scattered radiation as an alternative to the usual site-diversity schemes for ameliorating rain attenuation. The work is being guided by our earlier analyses of atmospheric optical communications, which showed that the largest performance gains over direct-beam systems accrue to adaptive diversity-combiners.[1-3] Based on this experience the present program seeks to: establish a theoretical propagation/communication model for adaptive millimeter-wave systems; determine the structure and place bounds on the performance of optimum systems of this genre; deduce from the modeling and analysis phases what propagation characteristics (if any) require experimental verification or measurement, and what device-technology directions seem warranted to realize the benefits (if they are potentialy significant) of adaptive diversity combining.

Thus far, our work has been focused on the propagation-theory component of the above hierarchy. Using plane-wave transport theory, for the space-to-earth communication geometry, and numerical techniques developed in this program we have found[4] the scattered-to-direct-beam power ratio P_S/P_D vs. extinction thickness τ. For the parameter values given in Table 19.1, P_S/P_D vs. τ is shown in Fig. 19-1. This result reaffirms the notion that useful levels of scattered power may be available in severe extinction conditions.

Presently, the research on propagation is being continued to obtain angular spread, multipath spread, and Doppler spread predictions for the scattered radiation. Preliminary work has also begun on the communication-theory issues for these scattered-radiation systems.

References

1. S.R. Robinson, "Phase Compensation Receivers for Optical Communication," IEEE Trans. Commun. COM-25, 900-909 (1977).
2. J.H. Shapiro, "Imaging and Optical Communication through Atmospheric Turbulence," Chapter 6 in J.W. Strohbehn (Ed.), Laser Beam Propagation in the Atmosphere (Springer Verlag, Berlin, 1978).
3. J.H. Shapiro and C. Warde, "Optical Communication through Low-Visibility Weather," Opt. Engr. 20, 76-83 (1981).
4. J.J. Fratamico, Ph.D. Thesis Research, Department of Electrical Engineering and Computer Science, M.I.T., Fall 1981.

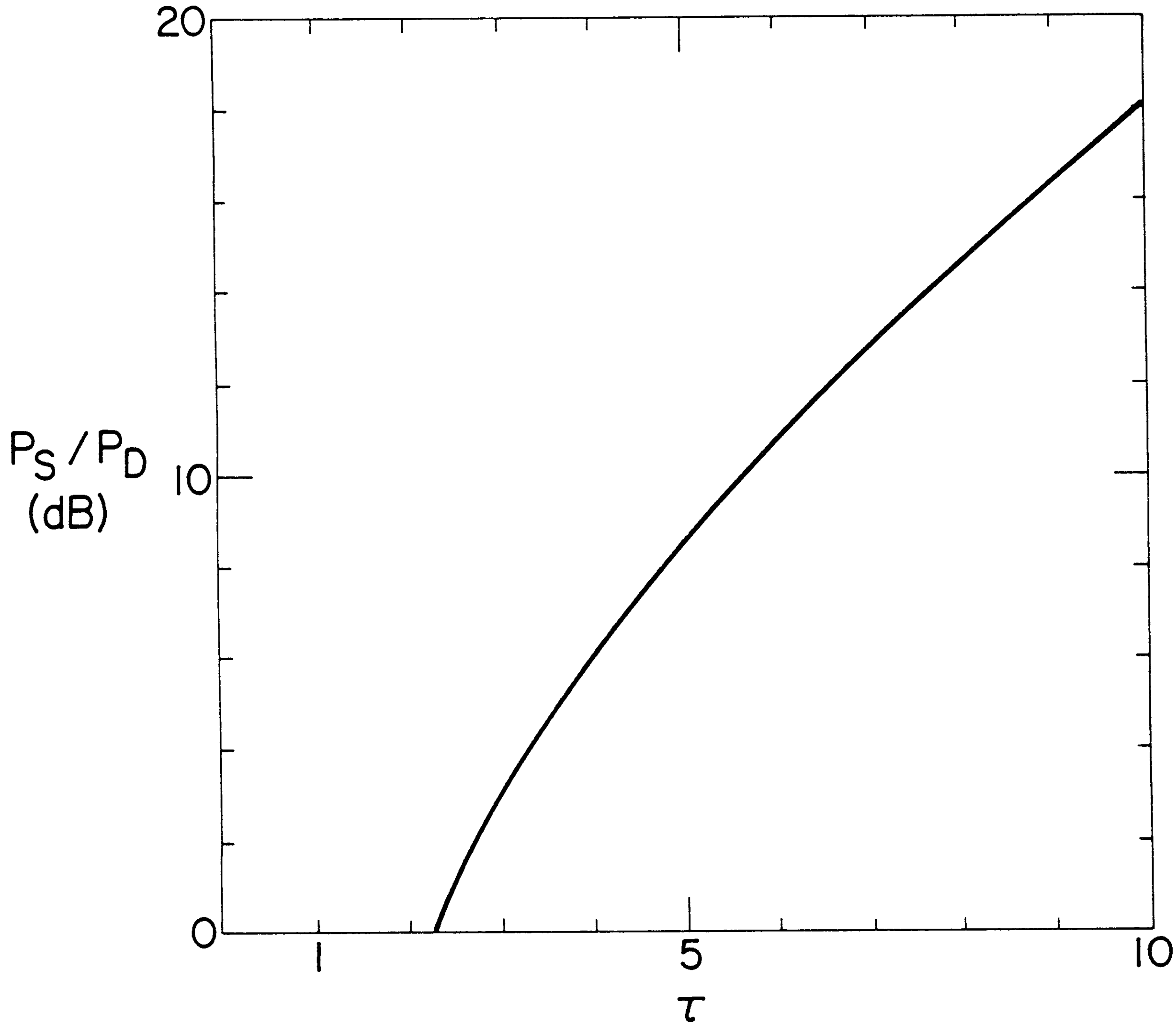


Figure 19-1: Scattered-to-Direct-Beam Power Ratio vs. Extinction Thickness

Table 19.1: Parameters for Scattered-Power Calculation

albedo	0.5
particle diameter/field wavelength (D/2)	2
scalar phase function	Mie theory

19.4 Fiber-Coupled External-Cavity Semiconductor High-Power Laser

U.S. Navy - Office of Naval Research (Contract N00014-80-C-0941)

Robert H. Rediker, Robert P. Schloss, Farhad Hakimi

The series combination of a semiconductor-diode gain element (a diode laser whose end facets have been antireflection coated) and an optical fiber has been placed inside an external cavity as illustrated in Fig. 19-2.

The external cavity operated with an output at a single wavelength whose width was less than the 1.7×10^{-5}-nm resolution of the scanning Fabry-Perot interferometer used. The spectrum illustrated in Fig. 19.3 is for a multimode optical fiber inside the cavity.

When a grating in the Littrow configuration is used as one of the cavity end reflectors, the spectral line can be tuned. Other elements such as a polarizer can also be placed inside the cavity at the fiber output to select the polarization of this output. With proper alignment of the elements inside the cavity, temporally stable operation of the external-cavity output is obtained, there are no spikes or fluctuations within the 225-Mhz bandwidth of the detection circuit, there is negligible modal noise as measured on a spectrum analyzer, and the drift in output which occurs over the order of several minutes is consistent with thermal variations expected in the experiment.

Similar results have been obtained with either a single-mode or multimode fiber in the cavity. The values of the threshold for stimulated emission have been measured and a model developed using these values and other diagnostic measurements to determine the insertion loss (including the coupling inefficiency) of the fibers. While the multimode fiber collects approximately 70 percent of the radiation and the single-mode fiber approximately 20 percent of the radiation from the diode gain element (and in other experiments from a diode laser from the same batch), the insertion loss of the multimode fiber is nearly the same as that of the single-mode fiber. This result is expected because only a selected mode (or selected modes) of the multimode fiber can participate in the laser action of the external cavity.

These results are similar to previously reported results for an external cavity without a fiber.[1] The stable cw operation reported here was achieved by the appropriate alignment of the elements inside

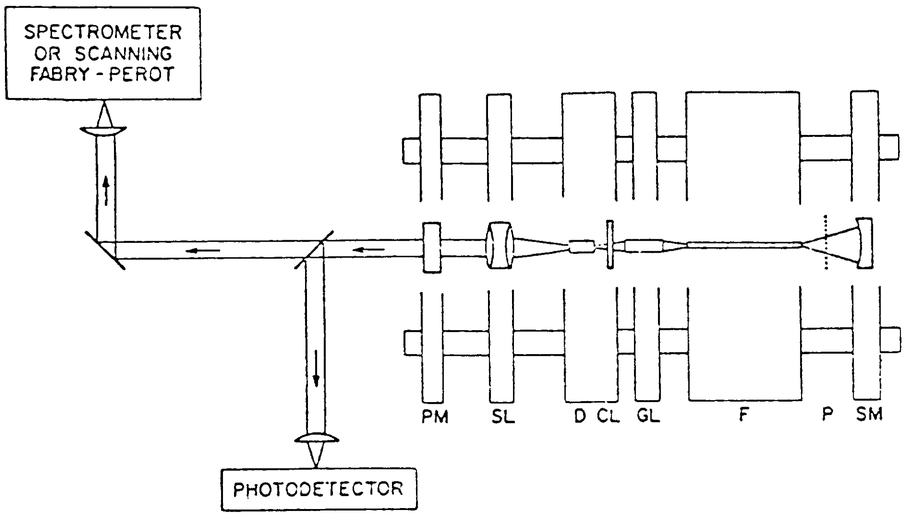
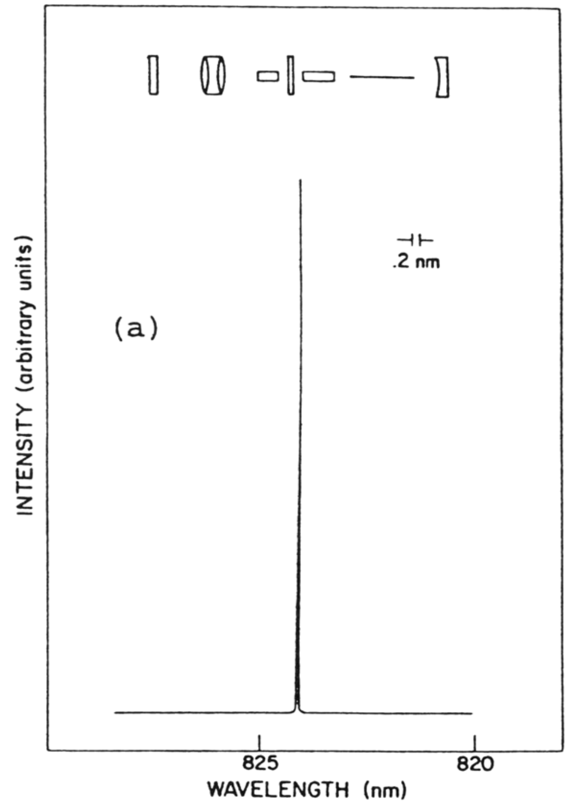


Figure 19-2: Optical layout of experiments. External-cavity laser components are shown in a top, cutaway view through the four-bar Super-Invar supporting structure. The labeled elements are: PM - plane mirror; SL - spherical collimating lens; D - diode gain element; CL - 40-mm diameter cylindrical lens; GL - graded-index (GRIN) rod lens; F - 14-cm-long optical fiber; P - polarizer; SM - spherical mirror. The polarizer was removed for some experiments. The plane mirror (PM) was replaced by a grating in the Littrow configuration in other experiments (the output in this case was the zero order of the grating).

our cavity, and differs from the more complex behavior reported for the combination of a diode laser and a fiber used as an "external cavity.[2,3]

The experiments reported here are aimed towards demonstrating the feasibility of coupling semiconductor-diode lasers in parallel by using optical fibers and thus verifying the concept of a laser system with average power up to the order of kilowatts (see Fig. 19-4). The fibers are required so that the diode lasers (actually gain elements) can be used in subgroups "remote" from the cavity to reduce the power-dissipation density.

Since the electromagnetic mode of a semiconductor-diode gain element (laser) is TE and the



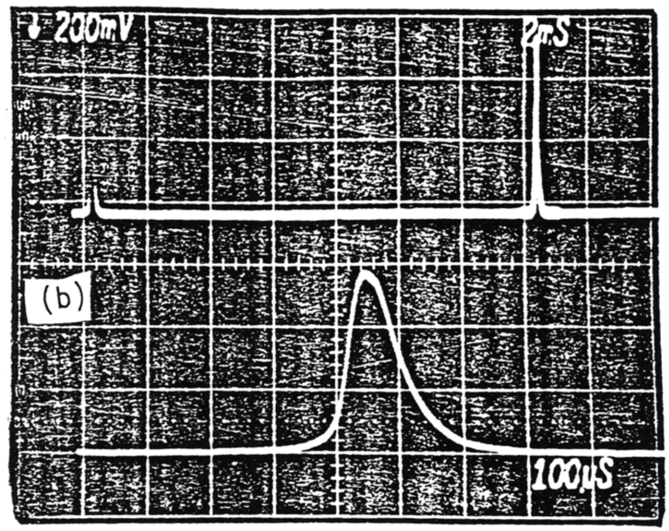


Figure 19-3: (a) Spectrum of stimulated emission output of external cavity containing series combination of a diode gain element and a multimode fiber. (b) Fabry-Perot scan of this spectrum. Top trace shows entire 1500-MHz instrument resolution. These results are typical for output powers up to the 2-mW level set by diode life considerations.

electromagnetic mode of an optical fiber is HE, both different from the free-space mode, it was important to make certain that the combination of semiconductor-diode gain element and optical fiber performed appropriately in an external cavity. The results presented in this report demonstrate that this combination does perform appropriately.

References

1. M.W. Fleming and A. Mooradian, "Spectral Characteristics of External-Cavity-Controlled Semiconductor Lasers," IEEE J. Quantum Electron. QE-17, 44 (1981).
2. I. Kushima and M. Maeda, "Lasing Spectra of Semiconductor Lasers Coupled to an Optical Fiber," IEEE J. Quantum Electron. QE-15, 844 (1979).
3. L. Figueroa, K.Y. Lau, H.W. Yen, and A. Yariv, "Studies of (GaAl)As Injection Lasers Operating with an Optical Fiber," J. Appl. Phys. 51, 3062 (1980).

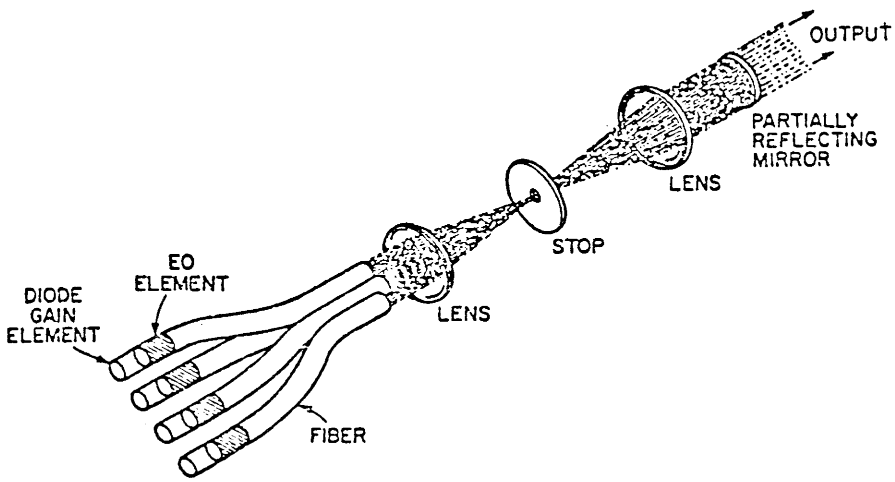


Figure 19-4: Concept of fiber-coupled external cavity semiconductor high-power laser illustrating from left-to-right: the semiconductor-diode gain element whose left facet is coated for near-unity reflectivity and whose right facet is antireflection coated; electrooptic element for phase shifting; focusing lens; the appropriate spatial filter to assure coherence of wavefront across entire fiber bundle emitter (illustrated schematically as a stop); focusing lens to recollimate beam; and a partially reflecting mirror. The external cavity is bounded on the left by the reflecting facets of the semi-conductor gain elements and the right by the partially reflecting mirror.