9A-4 Laser Action by Enhanced Total Internal Reflection,[1] Charles J. Koester, *Research Division, American Optical Company, Southbridge, Mass.*

Oscillation and amplification have been observed in a fiber in which the core is passive glass and the cladding is neodymium doped glass. As in conventional fiber optics, the refractive index of the core is greater than that of the cladding, so that light is carried in the core by total internal reflection. The results are interpreted as meaning that the reflection coefficient at the interface between passive core and laser cladding is greater than unity. Expressed in waveguide terminology,[2] modes which are guided by the high-index passive core but have a substantial portion of their energy in the cladding can be amplified by means of an active cladding.

In the fiber configuration the core was clear glass, 8 μm in diameter, refractive index 1.529. The first cladding was 5 weight percent neodymium doped barium crown glass,[3] 26 μm outside diameter, refractive index 1.509. A second cladding of clear glass was added for mechanical strength; outside diameter 1.5 mm, refractive index 1.510. Because of the index relationship, $n_2 < n_3 < n_1$, light guide action by total internal reflection occurs only in the core, not in the active cladding.

When a 44 cm straight length of this fiber with normal ends was placed adjacent to a straight flash lamp which was pulsed with 2900*j*, oscillation occurred. The near field was photographed by using a 40X microscope objective to image the fiber end of an infrared sensitive plate.

The photograph showed that nearly all the energy emerged from the passive core, only a small and rapidly decreasing amount appearing outside the core-cladding interface.

The far-field pattern exhibited a null on axis, with most of the energy appearing in hollow cones of half angle 3.6° and 12.1°.

The interpretation is that when radiation at 1.06 μm is reflected at the core-cladding interface, the portion which penetrates beyond the boundary produces stimulated emission. The net effect is a reflection coefficient at the core-cladding interface which is greater than unity. The reflection coefficient should be related to the depth of penetration of the radiation into the laser cladding; therefore the coefficient should increase as the angle of incidence decreases from grazing to the critical angle. This leads to the observed hollow cone output pattern. In the mode description, those modes close to cutoff should be favored over those far from cutoff, since those close to cutoff have a larger fraction of their energy in the cladding.

The fiber was also used as an amplifier in a manner similar to that used with active core fiber lasers.[4] A gain of 3 percent per cm was observed with the passive core fiber laser. Calculation of the reflection coefficient at oblique incidence on the interface between passive and active media will be discussed.

One advantage of the active cladding method for obtaining stimulated emission is that it does not require high optical quality in the active material. Total internal reflection will be maintained so long as the index of the core is greater than the material with which it is in contact, and the latter is nonabsorbing. Therefore bubbles, small index variations, and inclusions in the cladding will be of little or no consequence. Furthermore, the active cladding in principle is not limited to glass, but can be liquid, gas, or any solid material which makes optical contact with the passive core.

[1] Work supported in part by the U. S. Air Force Systems Command, Rome Air Development Center, Griffiss AFB, N. Y.
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[3] E. Snitzer, *Phys. Rev. Lett.*, vol. 7, p. 144, 1961. See also *J. Appl. Phys.*, vol. 32, p. 36, 1961.
[4] C. J. Koester and E. Snitzer, *Appl. Opt.*, vol. 3, p. 1182, 1964.

9A-5 Wide-Field Active Imaging, R. A. Myers, H. Wieder, and R. V. Pole, *IBM Watson Research Center, Yorktown Heights, N. Y.*

In this paper we report the results of some experiments in active imaging—image processing in which the pictorial information is placed within the laser cavity. By the use of an active medium which provides high gain over a wide aperture in conjunction with a highly degenerate conjugate resonator, we have been able to obtain diffraction-limited resolution with an information content orders of magnitude greater than previously reported.[1] The resonator used is the Flat-Field Conjugate Resonator (FFCR),[2] which can support as many as 10^7 modes of nearly equal Q when properly designed lenses are used.[3] As active medium we used the pulsed hollow cathode Hg^+ laser, as described by Byer et al.[4]

In the present FFCR, two plane mirrors are imaged one upon the other by means of two achromatic doublets (focal lengths about 200 mm) located between the ends of the discharge tube and the mirrors. Active imaging is accomplished by masking one of the mirrors and observing the pattern resulting on the other mirror. Masks used include pinholes, wire meshes, photographic transparencies (including an Air Force resolution target), and phase objects such as bleached holograms, as well as patterns etched in thin metallic films that were used directly as mirrors. The mode pattern could be observed both photographically and directly by means of a telescope or microscope.

Several hollow cathode geometries were used, in an effort to optimize the gain, numerical aperture, and degeneracy of the laser, but most data were obtained with a hollow cathode 200 mm long and 25 mm in diameter, in which the single-passgain was measured to be as high as 9 dB. With the doublets working near $f/10$, the resolution over a 15-mm-diameter field was greater than 100 lines/mm, which corresponds quite well to the observed resolution of the passive system. The resonator was thus capable of actively imaging photographic transparencies having more than 10^6 bits.

One characteristic of active imaging in this type of resonator is that all the modes have a large common active volume, and the suppression of some of the modes enhances the intensity of the others. Furthermore, the nonlinear behavior of a laser as an oscillator allows sharp discrimination between differing loss levels in the cavity. These effects have been observed, and their possible application to contrast enhancement and image dissection will be discussed.

[1] W. H. Hardy, *IBM J. Res. and Dev.*, vol. 9, p. 31, 1965.
[2] R. A. Myers and R. V. Pole, *J. Opt. Soc. Am.*, vol. 55, p. 1574, 1965.
[3] J. S. Wilczynski and R. E. Tibbetts, *ibid.*
[4] R. L. Byer et al., to be published. We thank these authors for making this report available to us.

9A-6 Focusing Properties of a Single-Mode Laser Beam at Small *f*-Numbers, A. L. Bloom, *Spectra-Physics, Inc., Mountain View, Calif.*

We have made a computer analysis of the energy distribution, around the focal point, of a focused laser beam having a Gaussian intensity profile and focused by a small *f*-number system. The analysis was based on the solution of Maxwell's equations for a converging plane-polarized spherical wave developed by Richards and Wolf[1] and by Boivin and Wolf.[2] The theory for aplanatic focusing (in which a plane wave is converted directly into a spherical wave at a spherical surface) was essentially the same as that of Boivin and Wolf[2] except for substitution of the Gaussian profile for the uniform intensity distribution used by them. In addition to aplanatic focusing, we have also computed for two other types of focusing that may be of practical importance. They are 1) gradual conversion of a plane wave to a spherical wave (denoted hereinafter as the "uniform sphere" case), and 2) focusing of a plane wave by a parabolic mirror.

The results in the focal plane show that, at *f*-4, scalar wave theory may be used with confidence and it is a moderately good approximation even at *f*-2. (The *f*-values are defined between the $1/e$ intensity points of the incident Gaussian plane wave.) At *f*-1, however, the focused spot is no longer circular but is elongated in the direction of *E*-vector polarization by the presence of a component polarized along the optic axis.[2] In addition, the central intensity is depressed relative to that predicted by theories valid for large *f*-numbers. These effects are particularly noticeable in the uniform sphere and parabolic mirror cases, in which a relatively large fraction of the energy arrives at large angles to the optic axis. Nevertheless, despite these effects, it appears to be possible to design an optical system in which most of the energy is concentrated into a region one wavelength across.

The computation also gave relative intensities along the optic axis near the focal plane. It was found that the depth of focus of a focused Gaussian is considerably less than that of a focused uniformly illuminated aperture, a result that can be

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[2] A. Boivin and E. Wolf, *Phys. Rev.*, vol. 138, pp. B1561, 1965.