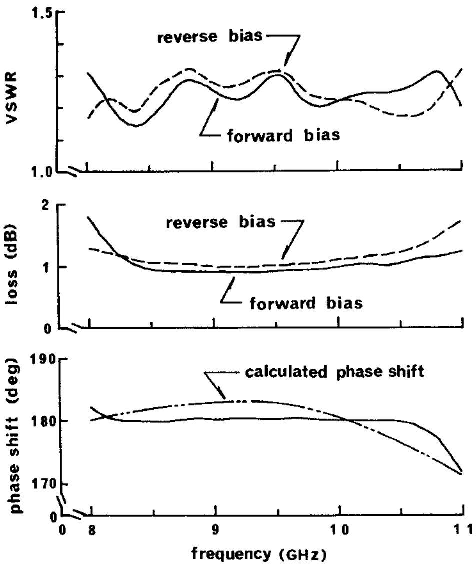

Fig. 7. Observed performance of the X band reflection-type 180° phase shift section.

photolithographic techniques. Its input and output ports are isolated from each other in the dc circuit. But these disadvantages have no serious influence on the phase shifter realization.

The 180° phase shift section described here is very well suited for X band broad-band phase shifters realized in an integrated circuit medium as may be required in a phased array radar.

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Laser Fiber Coupling with a Hyperbolic Lens

K. KUROKAWA, FELLOW, IEEE, AND E. E. BECKER

Abstract—**Substantial improvements in the coupling efficiency from injection lasers to multimode glass fibers have been obtained by spherical lenses melted on the fiber ends. However, the spherical lens has its own drawbacks. It excites high-order modes which are slow and lossy and it becomes less effective when used with graded-index fibers such as Selfoc. This paper proposes a hyperbolic lens which, in principle, is free from these drawbacks. Several samples have been made by first grinding one end of each fiber in a wedge form and then mechanically or flame-polishing the ground surface. These preliminary samples improved the coupling efficiency by a factor of 2–5 over the simple flat-end coupling depending on the difference in the refractive indices of the core and cladding. The improvement is slightly better than that achieved by spherical lenses.**

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The authors are with Bell Laboratories, Murray Hill, N. J. 07974.

I. INTRODUCTION

GaAs double-heterojunction lasers have broad radiation patterns in the plane perpendicular to the junction plane. On the other hand, glass fibers useful for communication applications have narrow acceptance angles. Consequently, when a double-heterojunction laser and glass fiber are put together, only a small fraction of the output power from the laser is usefully coupled into the fiber for transmission. In other words, the coupling efficiency is poor. Several methods have been proposed to improve the coupling efficiency. Cohen [1] first proposed using a cylindrical lens glued to the flat end of a fiber. Later, Cohen and Schneider [2] reported good results obtained with spherical and cylindrical microlenses made from photoresist material. Their work is primarily addressed to single-mode or low-order mode fibers. Independent of this work, Kato [3] proposed a spherical lens fabricated by melting the coupling end of a multimode glass fiber. Although its application is limited to multimode glass fibers, the melted-on spherical lens has a great advantage in that the fabrication is particularly easy.

The theory of the spherical lens has been worked out in detail by C. A. Brackett [4]. In addition to its advantages, the theory indicates that the spherical lens has the following drawbacks.

1) When the core radius becomes small compared to the radius of curvature of the lens, which is essentially equal to the outer radius of the fiber, the improvement of the coupling efficiency becomes small.

2) The spherical lens excites high-order modes which are slow and lossy.

3) The spherical lens becomes less effective when used with graded index fibers such as Selfoc.

This short paper proposes a hyperbolic lens, which is, in principle, free from these drawbacks.

First, the equation of the lens surface will be derived which makes all the rays emitted from a point source and refracted into the glass fiber parallel to the fiber axis. Then the method of calculating the coupling efficiency will be briefly presented, and finally the lens fabrication and efficiency measurements which we have used will be described together with the experimental results.

Admittedly, our fabrication method is still crude but the results already indicate that the hyperbolic lens is worth considering when GaAs injection lasers are to be used in fiber transmission systems.

II. EQUATION OF LENS SURFACE

In this section, the equation of the lens surface is derived which makes all the rays emitted from a point source and refracted into a fiber parallel to the fiber axis. Referring to Fig. 1 the point source is located at 0. The ray emitted from the point source is incident to the lens surface at $\rho(\varphi)$ where φ is the emission angle with respect to the axial direction of the fiber. The incident and refracted angles, θ_1 and θ_2, are related to the refractive index n of the fiber

$$n = \sin \theta_1 / \sin \theta_2. \tag{1}$$

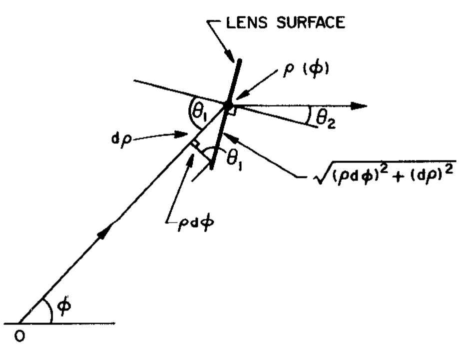

Fig. 1. Derivation of the equation of the lens surface which makes the refracted rays all parallel to the fiber axis.

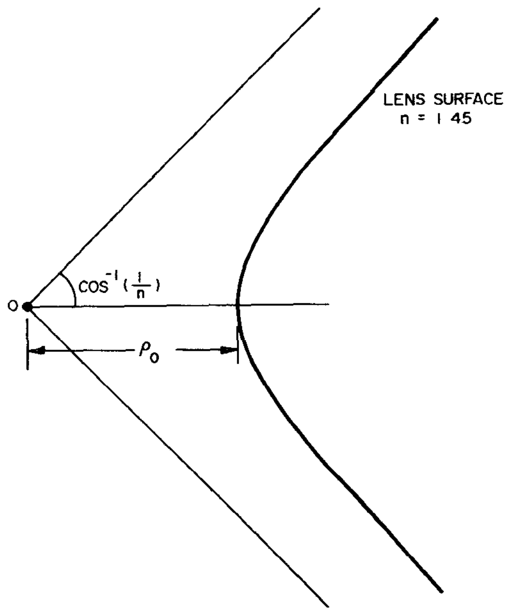

Fig. 2. The desired hyperbolic lens profile ($n = 1.45$).

Considering the infinitesimal triangle shown in the figure, $\sin\theta_1$ and $\sin\theta_2$ are given by

$$\sin\theta_1 = \frac{d\rho}{[(\rho\, d\varphi)^2 + (d\rho)^2]^{1/2}} \tag{2}$$

$$\sin\theta_2 = \sin(\theta_1 - \varphi) = \sin\theta_1 \cos\varphi - \cos\theta_1 \sin\varphi$$
$$= \frac{d\rho \cos\varphi - \rho d\varphi \sin\varphi}{[(\rho d\varphi)^2 + (d\rho)^2]^{1/2}}. \tag{3}$$

Eliminating θ_1 and θ_2 from (1)–(3) gives

$$\frac{d\rho}{\rho} = \frac{n \sin\varphi}{n\cos\varphi - 1}\, d\varphi. \tag{4}$$

From (4), the equation of the desired lens surface is given by

$$\rho = \frac{K}{n\cos\varphi - 1} \tag{5}$$

where K is an integration constant. The desired surface is hyperbolic as shown in Fig. 2, with the asymptote given by

$$\varphi = \pm \cos^{-1}(1/n) \tag{6}$$

and the distance from the origin to the lens apex by

$$\rho_0 = K/(n-1). \tag{7}$$

III. COUPLING EFFICIENCY

The radiation patterns of injection lasers are narrow in the junction plane. Consequently, the lens action is necessary only in the plane perpendicular to it. This means that a cylindrical lens is adequate for the laser-fiber coupling and that the coupling efficiency can be estimated by considering only two-dimensional effects of the hyperbolic surface.

Not all the power incident to the lens surface becomes the useful power for transmission. A part of the incident power is reflected at the lens surface and those rays which are incident on the cladding will be lost. To take these effects into account, the transmission coefficient $T(\varphi)$ of the lens surface is calculated as a function of φ and plotted in Fig. 3, assuming that the laser oscillation is in the TE mode as is usually the case. The limitations imposed by the finite radius of core are indicated by x and 0 on the curve for core radius r_c equal to ρ_0 and $2\rho_0$, respectively.

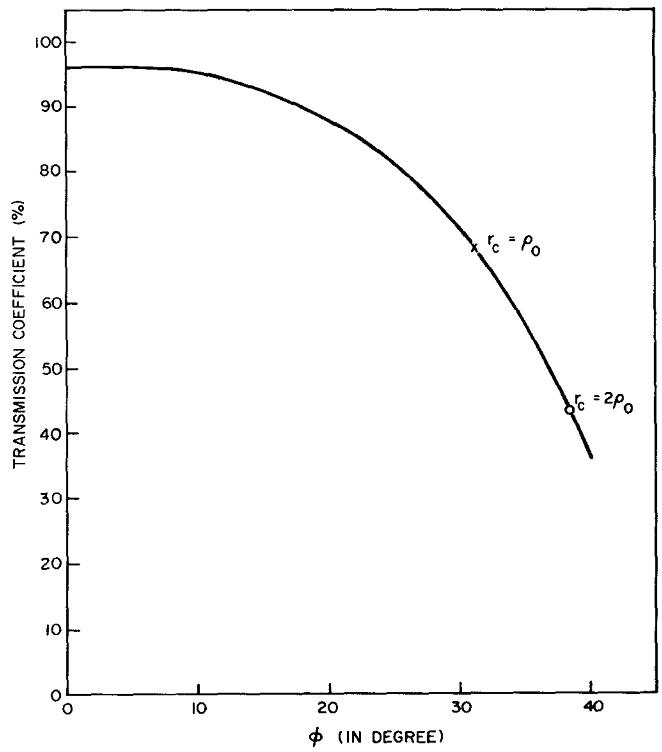

Fig. 3. Transmission coefficient $T(\varphi)$ at the lens surface as a function of the emission angle φ with respect to the fiber axis.

If the laser radiation pattern is given by $I(\varphi)$ the coupling efficiency is given by

$$\eta = \int_{-\varphi_{max}}^{\varphi_{max}} I(\varphi) T(\varphi)\, d\varphi \Big/ \int_{-\pi}^{\pi} I(\varphi)\, d\varphi \tag{8}$$

where φ_{max} is the maximum acceptance angle limited by the finite core radius. Using the theoretical pattern of GaAs–$Ga_{0.7}Al_{0.3}As$ double-heterojunction lasers with 0.18-μ active layer [5], η is calculated to be 69 percent for $r_c = 2\rho_0$ and 65 percent for $r_c = \rho_0$, regardless of $\Delta n/n$ of the fiber where Δn is the difference in the refractive indices of the core and cladding. Note that the radiation pattern in the junction plane is assumed to be narrow compared to the acceptance angle of this fiber which is determined by $\Delta n/n$. Fig. 4 shows the theoretical coupling efficiency of flat-end coupling with the same laser as a function of $\Delta n/n$. From this, a substantial improvement in the coupling efficiency is expected with the hyperbolic lens when $\Delta n/n$ is small. Experimentally obtained ranges are also indicated in Fig. 4, which will be explained in Section IV. In the preceding calculation, the source is assumed to be at the origin. When the source is displaced from the origin, the coupling efficiency will be affected in the following two ways.

1) The transmission coefficient $T(\varphi)$ will change because the incident angle into the lens surface will be different for a given φ.

2) The rays in the core will no longer be parallel to the fiber axis and if the angle $|\gamma|$ of the refracted rays with respect to the axis becomes larger than the critical angle $|\gamma|_{max}$ necessary for the total reflection at the core-cladding interface, those rays will be lost to the cladding. However, a detailed calculation shows that the source location is not over critical for good coupling. For example, if the source is displaced by 40 percent of ρ_0 toward the lens apex, the coupling coefficient becomes 71 percent for $r_c = \rho_0$ provided $\Delta n/n >$ 0.3 percent.

IV. EXPERIMENTS

A quartz capillary tube is used to hold a thin, fragile glass fiber during grinding and lapping operations. The glass fiber is inserted into the quartz capillary tube and cemented in place with quartz

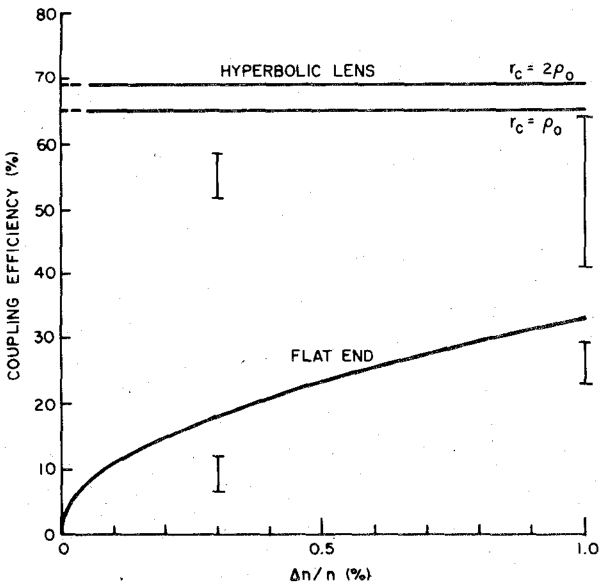

Fig. 4. Theoretical coupling efficiencies as functions of $\Delta n/n$ for hyperbolic lens and flat-end coupling. A typical radiation pattern of GaAs injection laser is assumed.

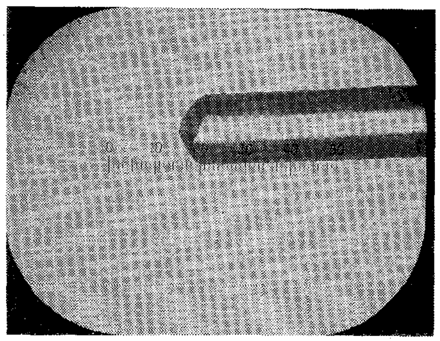

Fig. 5. A mechanically polished sample (soda-lime-silicate).

and one end is ground into a wedge form using a Norton abrasive wheel mounted on a Buehler metallurgical lapping machine. The final lapping and polishing are done on a politex lapping disk using 3-μ aluminum oxide abrasive. Fig. 5 shows a mechanically polished sample. For flame-polished samples, the fiber is first ground into a wedge shape as before and then melted (flame-polished) to form a cylindrical lens.

Coupling measurements are made using a GaAs injection laser operating on a pulse basis. A 20 ~ 25-cm piece of the fiber under test is coated over its entire length with black India ink to act as a stripping agent. Its effectiveness was carefully checked using both near-field and far-field measurements and the contribution of the cladding modes was found to be negligible (less than 3 percent). The end with the lens is placed in an x,y,z positioner with the wide plane of the lens parallel to the laser face and the other end against a power meter. The fiber lens position and angle are optimized for a maximum power meter reading. The ratio of this meter reading to the output power of the laser gives the coupling efficiency. The error due to the reflection from the power meter end of the glass fiber is neglected.

Using soda-lime-silicate glass fiber with core diameter 80 μ and $\Delta n/n = 0.3$ percent and quartz glass fiber with core diameter 39 μ and $\Delta n/n = 1$ percent, several lens and flat-end coupling experiments have been made. The range of coupling efficiency obtained with these samples is indicated in Fig. 4 in addition to the theoretical results. From this, it is seen that the coupling efficiency is improved by a factor of 5 for $\Delta n/n = 0.3$ percent and by a factor of 2 for $\Delta n/n = 1$ percent over the flat-end coupling. In comparison, spherical lenses fabricated on the soda-lime-silicate glass fiber ($\Delta n/n = 0.3$ percent) improved the coupling efficiency by a factor of 4 over the flat-end coupling when tested with a different GaAs injection laser having slightly narrower beamwidth than the present experiment [4].

V. CONCLUSION

A hyperbolic lens is proposed for improving the coupling efficiency between GaAs injection lasers and glass fibers. Several samples fabricated indicate that the proposed lens is practical for improving the coupling efficiency. No attempt has been made to fabricate a large number of lenses in one operation, but this does not seem difficult. Also no attempt has been made to make lenses on single-mode fibers, but our fabrication method indicates that very sharp wedges can be made on quartz fibers and hence the method can be readily extended to single-mode fibers.

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RF Cavity Irradiation Dosimetry

WILLIAM P. EDWARDS, MEMBER, IEEE, AND HENRY S. HO, MEMBER, IEEE

***Abstract*—A right circular cylindrical cavity designed to resonate at 380 MHz was developed to irradiate a monkey head with little or no radio frequency exposure to other tissues. The system is used in studies of the behavioral effects of the absorption of radiant power. Dose-rate measurements were made with an electrically equivalent calorimetric load, consisting of a saline-filled plastic cylinder whose geometry and position in the cavity reproduced cavity and transmission line parameters measured with a test animal. Since integral dose rate P_m (total power absorbed) is proportional to the net power transmitted to the cavity P_t, the constant of proportionality $K_m = P_m/P_t$ must account for the absorption of field energy by the tissue. K_m was determined by comparing the temperature rise produced in a fixed time period by the dissipation of dc power to the temperature rise produced by RF radiation in the same time period. It was found that, at an ambient temperature of 25±2°C and a relative humidity of 55±5 percent, K_m was 0.62.**

INTRODUCTION

Microwave heating may insult a variety of organ systems [1]. In addition, the existence of nonthermal bioeffects has also been sug-

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The authors are with the Biophysic Studies Section, the Division of Biological Effects, the Bureau of Radiological Health, Rockville, Md. 20852.