Further Investigations with an Optical Beam Waveguide for Long Distance Transmission

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Abstract—**Measurements made with an optical beam waveguide employing quartz lenses for the beam iteration demonstrate that a transmission loss of 0.5 dB/km is readily obtainable, and that this loss is solely determined by the absorption, scatter, and reflection losses of the lenses. The transmission loss and its variation depends on the air pressure along the light path. Photometric measurements of the energy distribution of the transmitted beam illustrate that distortions in the mode pattern of the laser are the major cause of the launching loss which for the available laser was measured to be approximately 0.4 dB.**

I. Introduction

SOME exploratory investigations on an experimental optical lens-type beam waveguide were reported previously.[1] The light path is enclosed in a 4 inch aluminum pipe which is supported above ground by wooden poles (see Fig. 1). The guide is 970 m long and comprises ten iterations at intervals of 97 m. The iteration is performed by quartz lenses of approximately 50 m focal length. The main conclusion from the first experiments was that the guide must be evacuated to eliminate fluctuations of the light beam which are caused by temperature movements of the air inside the guide. After the guide was modified to allow evacuation, a transmission loss of 1.0 dB at $\lambda = 0.6328\mu$ was measured.[2] This loss was still higher than expected, since the inherent lens losses (absorption, reflection, and scatter losses) which had been determined prior to their installation were only about 0.03 dB per lens. The diffraction loss of the fundamental beam mode caused by the lens apertures was negligibly small. There are three factors which could have caused the enhanced transmission loss. First, the reflection and scatter loss of the lenses have increased within the time period between the installation of the lenses and the performance of the transmission loss measurements; second, the laser beam mode was distorted or not properly matched to the guide, and third, the diffraction loss was enhanced by uncontrollable phase errors of the lenses, i.e., deviations from the phase transformation required for the iteration of the beam mode in the guide.

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[1] G. Goubau and J. R. Christian, "Some aspects of beam waveguides for long distance transmission at optical frequencies," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 212–220, March 1964.

[2] G. Goubau and J. R. Christian, "Loss measurements with a beam waveguide for long distance transmission at optical frequencies," *Proc. IEEE* (*Correspondence*), vol. 52, p. 1739, December 1964.

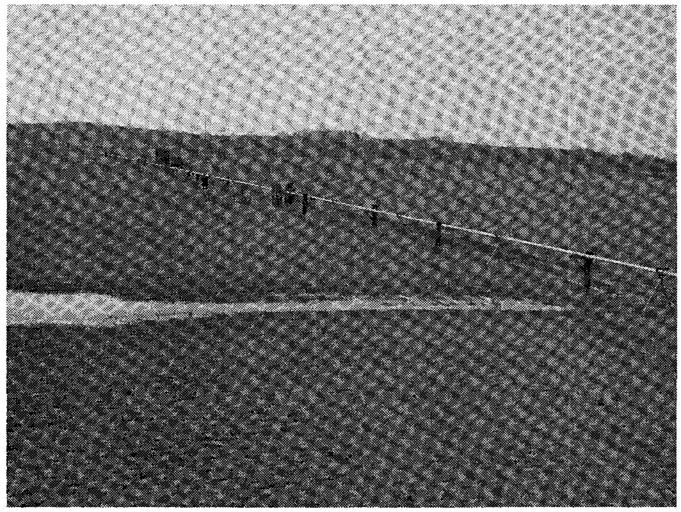

Fig. 1. Photograph of 970 m optical beam waveguide.

To determine the true causes of the enhanced loss, a new series of experiments were performed which included measurements of the intensity distribution of the transmitted beam, and investigations leading to the separation of the launching loss and the actual transmission loss. Furthermore, loss measurements were made at various air pressures in the pipeline to establish the maximum allowable pressure at which the transmission is unaffected by movements of the air along the light path.

Modification of the Guide

The lenses used in the previous series of experiments were replaced by similar, but somewhat larger, lenses (27 mm diameter compared with 22.6 mm) to allow the transmission of higher beam modes. The inherent loss of these lenses ranges between 0.03 and 0.05 dB. The reflection loss is considerably higher than specified by the supplier of the anti-reflection coating. A recheck of the inherent loss of the old lenses showed that this loss had increased from 0.03 dB to about 0.05 dB per lens. The reason for this increase was enhanced surface scatter. Apparently the lenses had been pitted by dust particles whenever the pipeline was filled with air.

Measuring Technique Used

The measurement of the intensity distribution in the beam was done by standard photometric techniques. The beam was photographed on film, with various exposures, using calibrated neutral density filters, and the density on the film measured with a micro-photometer.

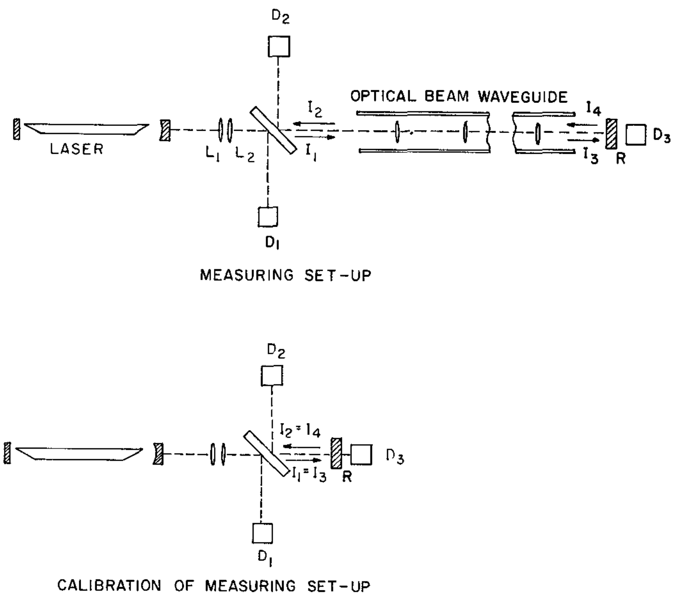

Fig. 2. Schematic of loss measuring setup.

The information on the launching loss was obtained by reflecting the beam at the end of the guide, and measuring the transmission loss for the forward and return trip of the beam. If the beam entering the guide does not have the appropriate field distribution, that is, if it contains higher modes, the forward loss is greater than the return loss because the higher modes have higher diffraction loss.

A schematic of the measuring setup is shown in Fig. 2. The laser beam is first transformed by a pair of lenses L_1 and L_2 to adopt it to the mode system of the guide. The lenses are slightly tilted to avoid errors in the measurements which occur if the reflections from these lenses are returned by the laser mirror and thus would enter the measuring setup. The tilt causes some astigmatic distortion with the result that the curvatures of the phase fronts within two perpendicular planes are not exactly alike. This introduces some ellipticity into the beam cross section but has no effect on the transmission loss.

Before the beam enters the guide, it is passed through a beam splitter which consists of a plane parallel glass plate. The mirror R at the end of the guide is partially transparent to allow for the measurement of the intensity of the passing beam I_3 by the detector D_3 which is located immediately behind the mirror. The intensity of the incident beam I_1 is measured by the detector D_1, and that of the returning beam I_2 by the detector D_2. The transmission loss in the forward direction of the beam is determined by the ratio I_1/I_3 and the loss on the return trip by the ratio I_4/I_2. The reflection factor of the beam splitter and the transmission factor of the mirror at the end of the guide are nearly equal. Therefore, the detectors, silicon solar cells, operate at approximately the same intensity level. To eliminate the effect of intensity fluctuations of the laser beam the detector outputs were measured with a ratiometer. The relations between the beam intensities and the detector currents i_1, i_2, and i_3 are as follows:

$$i_1 = c_1 I_1$$
$$i_2 = c_2 I_2$$
$$i_3 = c_3 I_3.$$

The three constants c_1, c_2, and c_3 are determined by the reflection and absorption factor of the beam splitter, the transmission factor of the mirror R, and the sensitivity of the solar cells. The quantities to be measured, I_1/I_3 and I_4/I_2, the transmission losses in either direction are given by

$$\frac{I_1}{I_3} = \frac{i_1 c_3}{i_3 c_1} \quad \text{and} \quad \frac{I_4}{I_2} = \frac{I_3 I_4}{I_2 I_3} = \frac{i_3 c_2 \Gamma}{i_2 c_3}$$

where Γ is the reflection factor of the mirror R. All the constants c_1, c_2, c_3 are eliminated by a simple calibration method which is illustrated in the lower half of Fig. 2. Mirror R and detector D_3 are moved to the input side of the guide. In this case $I_1 = I_3$ and $I_2 = I_4$, and the quantities c_3/c_1 and $c_2\Gamma/c_3$ are directly obtained from the ratios of the detector currents.

$$\frac{c_3}{c_1} = \frac{i_3}{i_1} \quad \text{and} \quad \frac{c_2 \Gamma}{c_3} = \frac{i_2}{i_3}\,.$$

Results

A. Measurements of the Intensity Distribution in the Beam

Figure 3 shows the fundamental beam mode at the input side of the guide (upper row), and at the end of the guide (middle row). The third row shows the first higher circularly symmetrical mode at the end of the guide. The three columns of photographs were obtained with 10, 20, and 30 dB calibrated neutral density filters inserted in front of the film (Kodak Plus-X). All photographs were made with the same exposure time of 1/15s, using a focal plane shutter.

The input beam has considerable distortions, which are primarily caused by internal reflections in the laser mirror. These distortions disappear in the output beam. However, due to the aforementioned tilt of the matching lenses L_1 and L_2 the output beam has elliptical cross section. The transmission of the higher mode (see lower row) of course, requires a different laser adjustment.

Figure 4(a), 4(b), and 4(c) show cross-sectional photometric scans of the photographs of Fig. 3. The irregularities of the incident beam are quite pronounced [Fig. 4(a)] and indicate the existence of a substantial launching loss. The intensity distribution of the fundamental mode at the output (i.e., after ten iterations) is practically a Gaussian distribution. The scan was made across the major axis of the elliptical beam. The higher mode [Fig. 4(c)] should have zero intensity in the center, but the resolution of the photometer was not adequate to establish the actual minimum.

B. Transmission Loss Measurements

The results of the transmission loss measurements are summarized in Table I. The return loss of the fundamental mode and that of the first ring-shaped mode are the same.

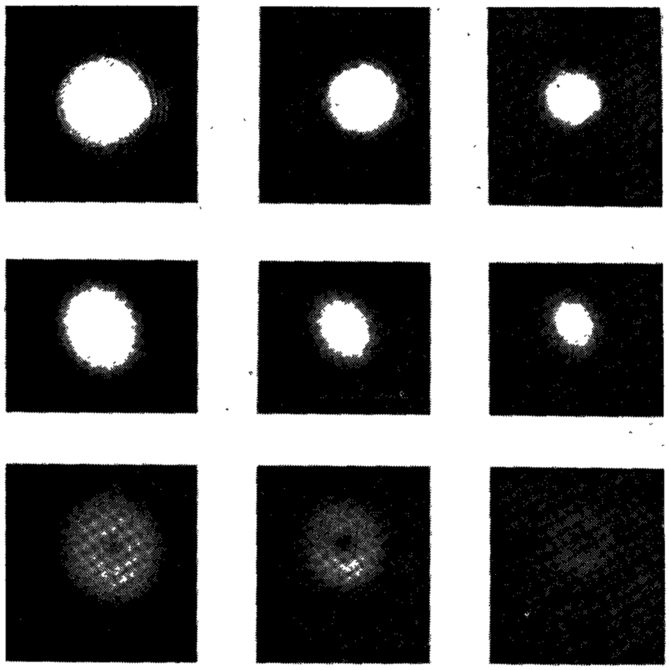

Fig. 3. Photographs of beam modes. Upper row: transmitted beam (laser output) at input of waveguide. Middle row: fundamental beam mode at output of waveguide. Bottom row: first circularly symmetrical mode at output of waveguide.

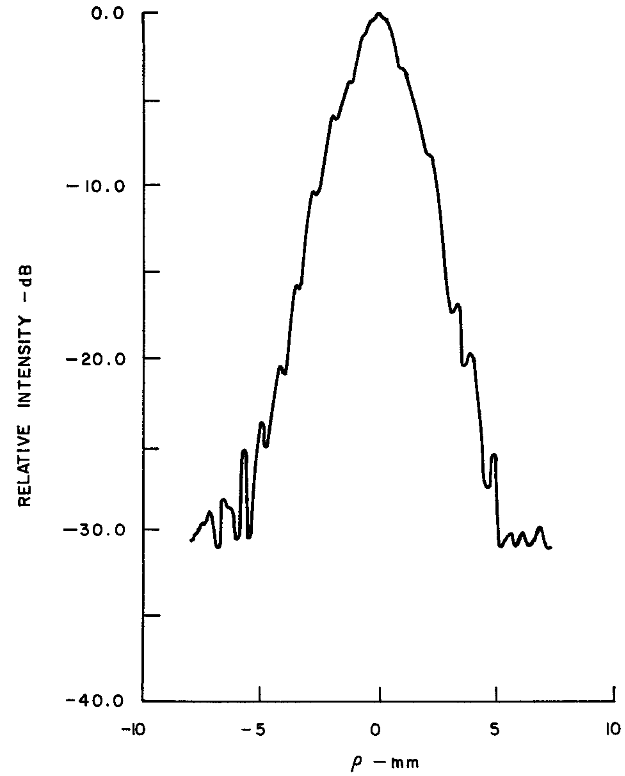

Fig. 4(a) Energy distribution of the transmitted beam.

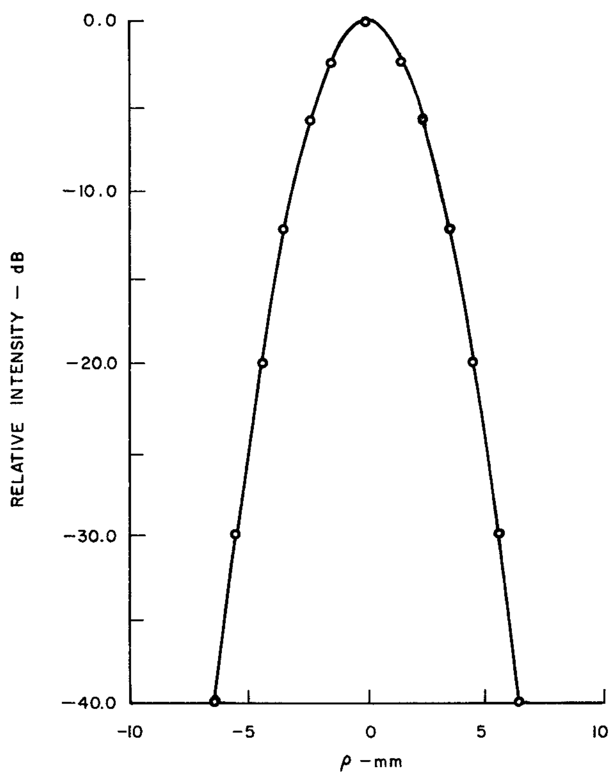

Fig. 4(b) Energy distribution of the beam mode at output of waveguide.

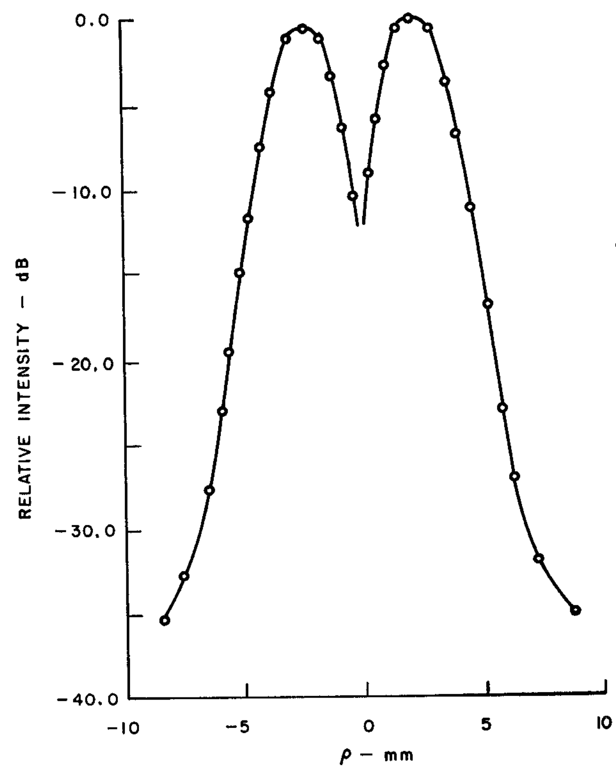

Fig. 4(c) Energy distribution of first circularly symmetrical mode at output of waveguide. ρ = distance from beam center.

TABLE I

MEASURED LOSS FOR OPTIMUM MATCHING BETWEEN LASER MODE AND GUIDED MODE

Inherent lens losses (reflection, scatter, absorption)
0.03 to 0.05 dB per lens
Diffraction loss < 10^{-4} dB

	Forward Loss	Return Loss	Launching Loss
Fundamental Mode	0.82 dB	0.42 dB	0.40 dB
First Higher Circular Symmetrical Mode	0.92 dB	0.42 dB	0.50 dB
Higher Combination Mode	1.22 dB	0.52 dB	—

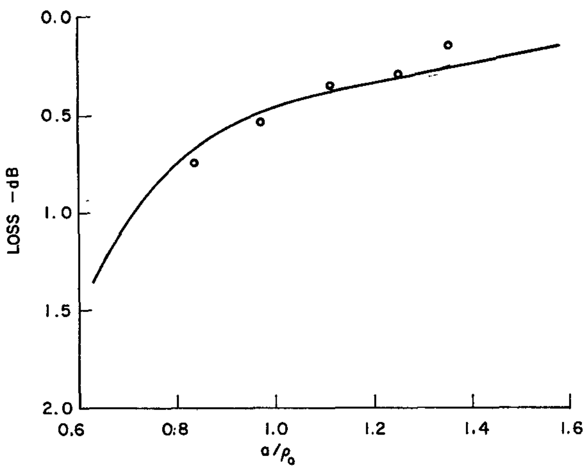

Fig. 5. Launching loss versus aperture limited input beam.

The lens apertures are large enough to pass both these modes without diffraction loss. The return loss of 0.42 dB is fully explained by the inherent loss of the ten lenses. This indicates that there is no enhanced diffraction loss due to phase errors of the lenses. The launching loss appears only in the forward propagation and is given by the difference between forward and return loss.

A beam with a more complicated field pattern showed a greater return loss which can be explained by the fact that the diffraction loss of the higher mode components is not negligible.

Figure 5 shows the increase in launching loss in dB if the input beam is limited by an aperture (a= radius of the aperture, ρ= mode parameter). The measurements were made with the laser adjusted for optimum fundamental mode transmission. The curve is calculated under the assumption that the three lowest circular symmetrical modes of the mode spectrum which is created by the aperture limitation are passed through the guide without diffraction loss while the higher modes are attenuated to the degree that their amplitude is negligible at the end of the round trip. The measured points justify this assumption.

C. *Effect of Air Pressure*

To reduce temperature gradients when the guide is filled with air, the 4 inch aluminum pipe which encloses the light path has been heat insulated with foam material and inserted in a 6 inch aluminum pipe. For air pressures below 50 mm Hg, the transmission is not noticeably affected by the presence of the air. Increasing air pressure requires some realignment of the laser because of the gravitational and thermal stratification of the air. Since the latter depends on the temperature exchange with the outside, the transmission loss is subjected to variations. Figure 6 shows three recordings of the round-trip loss at pressures of 200 and 400 mm Hg. The upper curve was recorded in the afternoon of an overcast day. The middle curve shows the transition period from an overcast to a clear day. (Note the increase in variation if the guide is exposed to direct sun radiation.) In both cases, the minimum loss was the same as for vacuum. The lower curve pertains to a pressure of 400 mm on a clear day. Here the minimum round-trip loss was about $\frac{1}{2}$ dB higher and the fluctuations were quite substantial. These fluctuations would, of course, be greater for longer guides. However, even for guides of many miles in length, a pressure of 10 mm Hg would be entirely adequate.

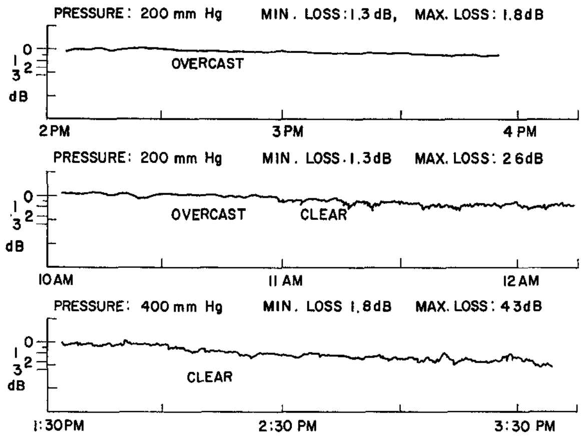

Fig. 6. Recordings of round-trip loss variations at various waveguide pressures and outside weather conditions.

CONCLUSION

In summarizing we can state that optical beam waveguides with quartz lenses yield transmission losses of less than 0.5 dB/km. The loss is determined by the inherent lens losses, in particular, by the reflection loss. If the guide includes bends, the loss will be somewhat higher due to the elements which are required to effect the bends, i.e., prisms or reflectors. Of course, the loss also increases if the lenses of the guide are misaligned. However, a simple mechanism has been developed for automatic realignment to compensate for movements of the ground which occur over long periods of time. This mechanism has recently been installed and will be described in a future paper.

The launching loss is a function of the laser beam and is of little consequence if the guide is several kilometers long.

The construction of beam waveguides does not require special techniques. The requirements for vacuum are minimal and present no technological problem. Evacuation may not be necessary at all if the guide is buried in the ground.