Pulse Shuttling in a Half-Mile Optical Lens Guide

By D. GLOGE and W. H. STEIER

To investigate the distortion of a gaussian light beam in a long lens guide a light pulse was shuttled back and forth up to 150 times in a straight underground conduit with lenses (quality λ/10) positioned confocally every 140 m. The pulse was formed by suddenly "dumping" the light stored in a He–Ne laser cavity into the guide. Part of the round-trip loss was replenished by a He–Ne amplifier. In scanning the intensity in the guide cross-section on various round trips of the pulse it was found that the gaussian profile was virtually undisturbed.

I. INTRODUCTION

Lens guides with widely separated glass lenses for long distance optical communication have been proposed in several varieties[1, 2] and investigated in various laboratory and field experiments.[3–5] The use of dielectric coatings reduces the loss to one per cent per lens or less,[3] an estimate which has been confirmed by the experiments reported here. This loss figure permits 1000 lenses to be placed in the beam path before the beam intensity is down by 40 to 50 dB and a repeater or amplifier is necessary.

An average distance of 100 m between lenses would lead to a repeater spacing of 100 km. There is legitimate doubt that a light beam can be kept bundled and centered on the guide axis over this distance. Measurements in a 140 m underground air-filled pipe showed a slow beam drift of several mm per week correlated with the ground temperature field.[5] Thermal insulation of the pipe could reduce this effect, but eventually along the line there will have to be some beam position control to cope with this and with an expected slow ground drift.

Careful investigation in the same pipe revealed that density fluctuations or any short time influence of the gas in a well-shielded conduit 5 feet below the surface can be neglected even over distances of 100 km.[7]

However, these measurements give no information about any time-independent distortion of the beam caused, for example, by imperfect lens surfaces. Abberations are most likely negligible for the low power lenses used in the lens guide, but random irregularities may lead to severe damage of the beam profile in a long sequence of lenses.[8, 9] This will impede detection, increase the diffraction loss, and hamper any active position control of the beam.

The difficulty of measuring these distortions lies in the sensitivity required. If 10 per cent deviation from the correct intensity profile of the beam is tolerable after 1000 lenses a check in one section has to be sensitive to 0.01 per cent deviation. In addition, this has to be done for many different lenses to gain a reasonable average. The shuttle pulse technique is one method for measuring these small deviations.

II. THE SHUTTLE PULSE LINE

A straight 3-½-inch-diameter iron pipe 5 feet below ground with lenses roughly every 140 m was used as a test line. The lenses had a focal length of 70 m, a diameter of 60 mm, a quality of $\lambda/10$, and antireflection coatings on both sides. There were six 140 m sections with a total length of about ½ mile. For further information about this line see Reference 5.

After a passage of 6 lenses no distortion of the beam could be measured reliably. To increase the minute effects involved the beam was folded back on itself, passing the same lenses many times. To distinguish between the various transits a light pulse shorter than the round trip travel time had to be launched. This "pulse shuttling technique" was used before[3] and was adopted here with some variations which are shown in Figure 1.

A polarization switch consisting of a KD*P crystal and a calcite Wollaston prism was positioned inside the cavity of a He-Ne laser oscillating at 6328Å. Activated by a voltage pulse this switch "dumped" the energy stored in the oscillator cavity into the test line. This light pulse passed through a He-Ne amplifier and a mode matching two-mirror telescope before entering the lens guide. When the pulse returned from its first round trip through the line it found no voltage on the switch, passed it once, and another time upon reflection from the mirror at the back of the switch, and entered the line once again.

On every reflection from one of the telescope mirrors about one per cent of the light pulse was transmitted and fed into a receiver. This loss and the loss in the switch were compensated by the He-Ne amplifier.* By counting the number of pulses in the receiver the number of round trips in the line was determined. The total loss in the line was calculated from the decay of the pulse train.

The use of a polarization switch to generate high power pulses from

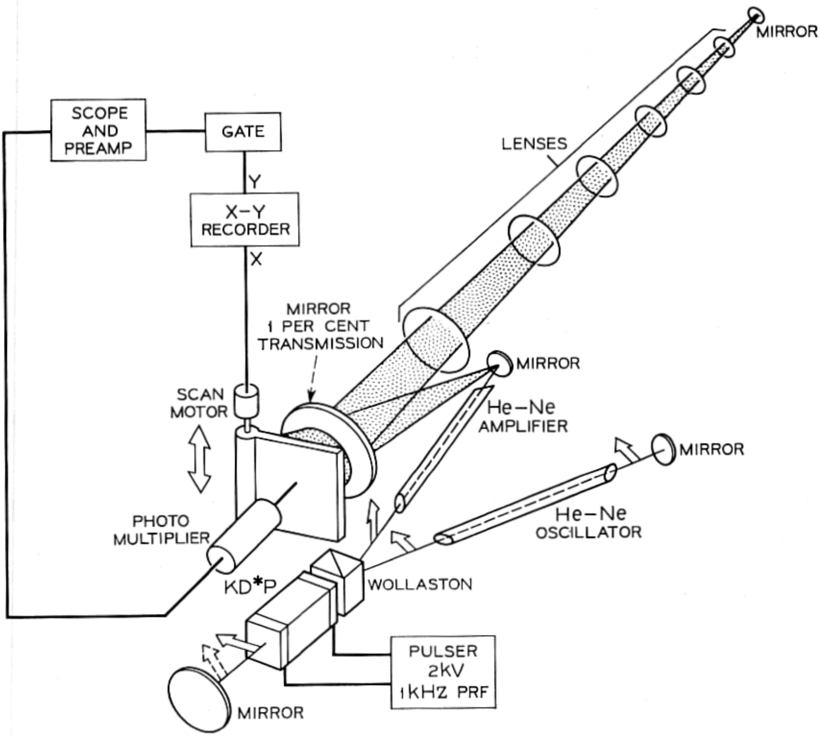

Fig. 1 — Shuttle pulse line showing pulse injection, receiver, and processing apparatus.

a He-Ne laser has been described before.[10] To reduce the losses in the switch both the KD*P crystal and the calcite prism were immersed in a matching oil chamber with antireflection coated quartz windows. Figure 2 shows the refractive indices for the polarization of the oscillator light. The z-cut KD*P crystal was $3 \times 3 \times 12$ mm, the longitudinal field was applied by silver-painted rims around both

* Its use was suggested by Mr. E. A. J. Marcatili.

ends. A loss of one or two per cent per transit may be expected for this switch.

The 2 m long oscillator cavity was almost confocal. An iris inside the cavity limited oscillations to the fundamental mode which had a 1/e diameter of 1.25 mm at the mirrors. The gas tube was 1 m long with a bore of 4 mm.

The 2 kV pulse from a commercial unit* had a rise time of 50 ns. During this time about half the oscillator light was rotated into the perpendicular plane of polarization and deflected into the shuttle pulse line by the Wollaston prism. The cavity was emptied com-

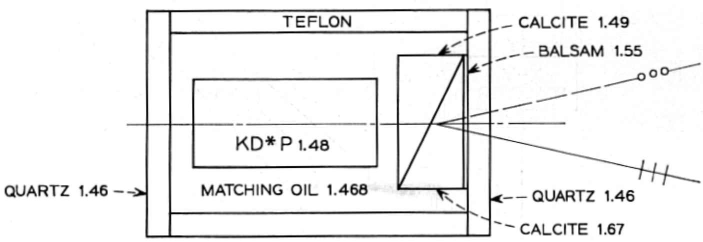

Fig. 2 — Optical switch with numbers giving the refractive indices for light polarized in the plane of the figure.

pletely after about 150 ns. The deflected pulse is shown in Figure 3. The peak power of the pulses entering the line was about 100 mw.[10]

The amplifier tube was 1 m long with a 4 mm bore. The telescope magnified the 1.25 mm diameter beam to the 10 mm diameter of the lens guide mode. The spacing of the telescope mirrors was 1.25 m, large enough to neglect spherical aberration and astigmatism. All mirrors used in the experiment had dielectric coatings.

As a necessary shield against turbulence the beam had to be enclosed everywhere. In the laboratory acetate tubes were used. In addition a wooden cover provided a shield against dust and acoustic vibrations. All parts of the launching system were mounted on a solid concrete table. The laboratory was an underground concrete room of 5×5 m. Air currents and convection in the underground conduit were prevented by an air-tight seal closing the tube where it entered the laboratory. One of the antireflection coated lenses already described was used for this purpose.

The mirror at the far end of the line had a 140 m radius of curva-

* Pulse Engineering Inc., Velonex Div. Model 350.

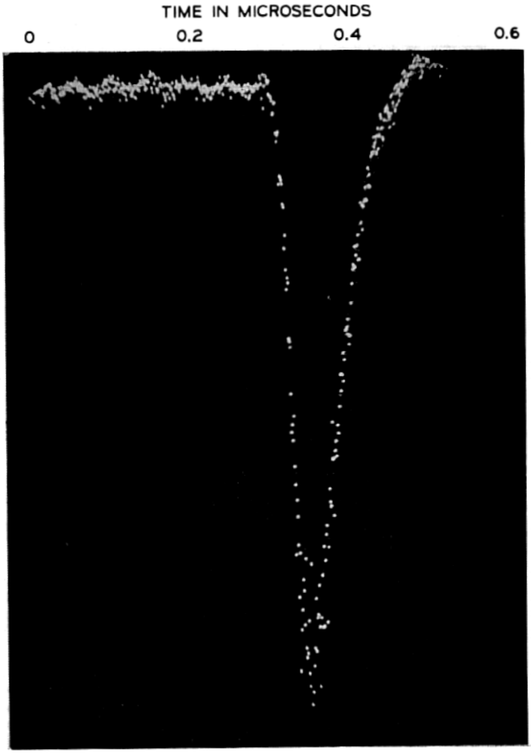

Fig. 3 — Pulse injected into the lens guide (amplitude not calibrated).

ture and was adjusted by remote control. It could be mounted in place of any of the lenses thus changing the guide length from 140 m to 6×140 m. The change in the decay rate of the pulse train was observed as the guide length was changed. From this it was concluded that each section added about 2 per cent to the round-trip loss of the pulses. Consequently there was about one per cent section loss per transit of which a large fraction can be attributed to the lenses. Notice that these lenses had been in use for about a year in previous field experiments where moisture and dust might have affected their coatings.

With the amplifier turned off the round-trip loss in the switch, the mirrors and the amplifier tube was about 18 per cent. The switch and the mirrors probably account for the largest part of the loss. The loss in the switch will be somewhat higher for the shuttle pulse polari-

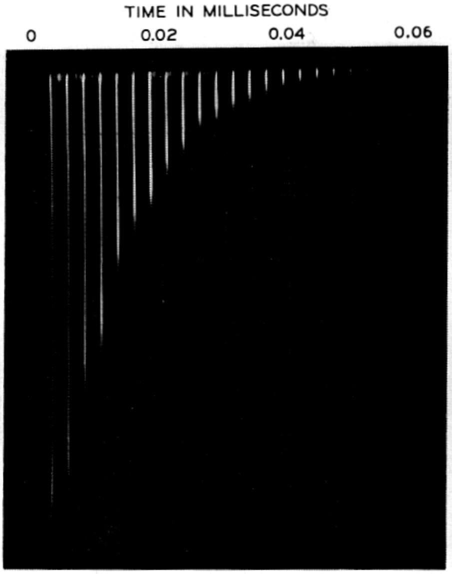

Fig. 4 — Pulse decay in the 3-section line with the amplifier turned off.

zation than for the oscillator polarization. For the perpendicular polarization of the shuttle pulse the indices in the calcite are interchanged from those shown in Figure 2, producing a larger mismatch. Figure 4 shows a pulse train received from a line with three sections corresponding to a round-trip loss of 24 per cent.

With the amplifier turned on, the 3-section line went into oscillation with modes up to the third order being observed. Though not as bright as in a cavity with one or two sections these modes were stable in time and showed no noticeable distortion of their intensity profile. Oscillating modes were a good indication for the optimum alignment of all components. In a line with more than three sections the gain was not sufficient to cause oscillations. Figure 5 shows a pulse train in a 3-section line after the amplifier gain was reduced enough to prevent oscillation.

The detection of the pulses was not limited by detector noise but by cw-light leaking from the switch into the cavity during the interval between pulses. If this light is at a resonant frequency of the shuttle pulse cavity a relatively large amount of power can be coupled from the oscillator and large field strengths will build up in the line. Fortunately this long cavity changes its length randomly during the round-trip time thus avoiding resonance. However, in this random case some power will still be coupled into the line and the oscillations will build up to an extent determined by the line losses. Therefore the amplifier gain had to be set to balance the background light and pulse decay so that a maximum number of pulses could be seen. This condition is studied quantitatively in the appendix.

Figure 6 shows the optimum round-trip loss, resulting in the maximum number of round trips N, for a given extinction ratio of the switch and a desired signal to noise ratio at the detector. The lines show the idealized situations of perfect resonance and completely random phase buildup. The experimental condition was somewhere in between, but close to complete randomness. To get the 150th pulse with an S/N of 20 dB, the amplifier gain was set for a round-trip loss of about one per cent. This suggests an extinction ratio of about 50 dB (see Figure 6). This extinction ratio has to be understood as the ratio of the peak pulse power to the power that leaks in between pulses and propagates in the line. Only the small part of the light leakage that is in the lower order modes can propagate.

The initial high amplitude pulses in Figure 5 suffered a larger attenuation than one per cent as they drove the amplifier into satura-

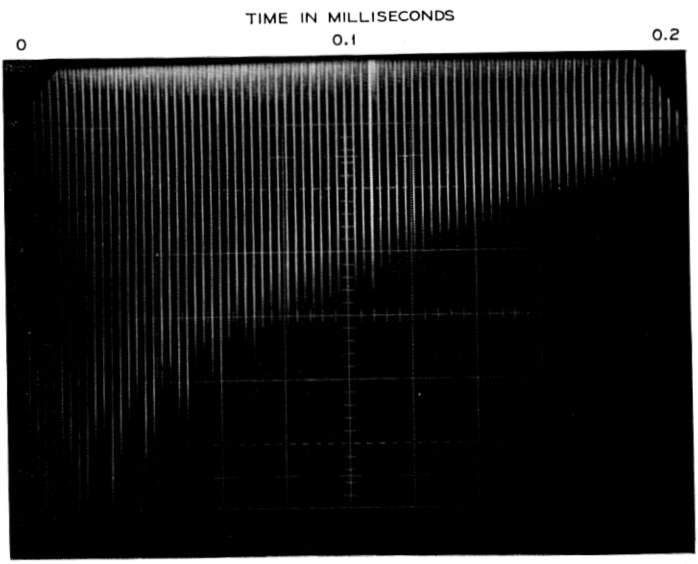

Fig. 5 — Pulse train from the 3-section line with the amplifier working.

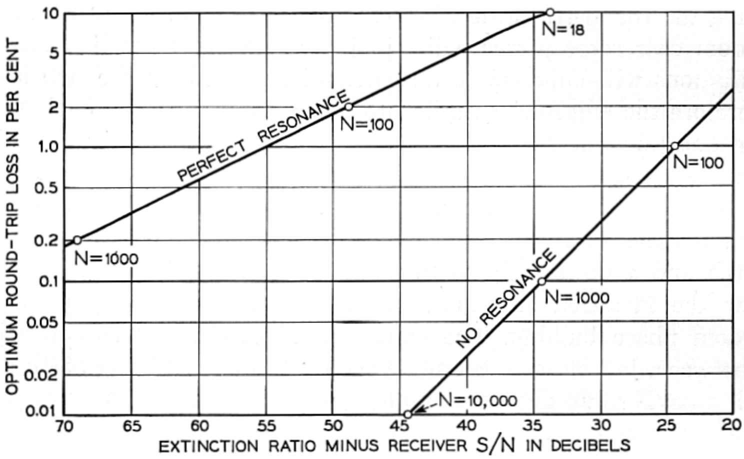

Fig. 6 — Round-trip loss versus extinction ratio of the pulse injector for the maximum number of pulses detectable. The lines indicate the limits of perfect resonance and of complete phase randomness.

tion. Some of the background light in Figure 5 is caused by acoustic resonances in the KD*P crystal following the high voltage pulse. Since this did not obstruct the detection of the initial pulses and vanished rapidly no measure was taken to prevent it.

III. THE SCANNING OF THE BEAM PROFILE

The light transmitted by the larger telescope mirror in Figure 1 was used to measure the lateral intensity profile of the light pulses impinging on this mirror. The technique was to measure the intensity at a certain point of the mirror with a pinhole receiver when, say, the 50th pulse comes by, then move to another point, launch a new pulse, and wait again for the 50th round trip. This can be repeated point by point for any detectable round trip. Since in the experiment the round-trip time was several microseconds a new pulse could be launched every millisecond.

The pinhole receiver consisted of a photomultiplier with a small iris and a diffusing ground glass plate behind it. The hole diameter was a fraction of a millimeter. The light pulses had a spot diameter of 10 mm at that mirror.

The multiplier received all pulses arriving from the far end of the line. The transmitted intensity from pulses traveling in the opposite direction was deflected to the side and did not reach the pinhole. A diode gate, triggered after the proper delay time, picked the wanted pulse out of the amplified multiplier signal. The signal from the gate was amplified by a narrow band resonance amplifier which was tuned to the 1-kHz repetition rate of the injected pulse. The rectified amplitude of the 1-kHz signal was displayed on the y-axis of an x-y recorder. The x-deflection corresponded to the location of the pinhole receiver which was moved slowly across the back of the mirror. One scan took several minutes, the scanning speed being determined by the bandwidth of the rectified signal. This bandwidth was reduced to a fraction of 1 Hz to suppress time dependent effects as far as possible. The accuracy of the scan was set by variations affecting the tremendously sensitive alignment of the system. This limited the reproducibility to about 5 per cent of the total signal.

Figures 7, 8, and 9 show scans taken in a line with three sections. The intensity units in these figures are arbitrary and different for each scan as the amplifier settings were changed between scans. All these scans were taken along a horizontal line across the center of the light beam. The dotted lines show a gaussian intensity distribution calculated for the theoretical 1/e-spot diameter of 10 mm for comparison.

Figure 7 represents a check of the profile launched into the line. The bumps and spikes on this scan are attributed to variations with

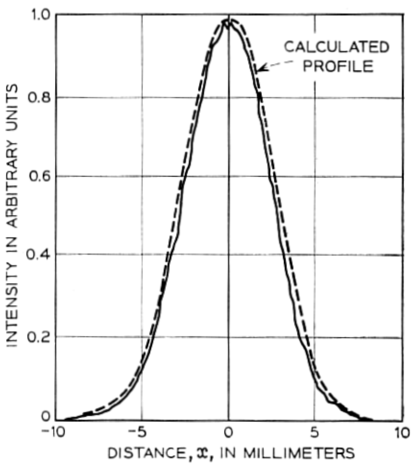

Fig. 7 — Intensity scan across the guide cross-section for light after one round trip in the 3-section line.

time and the injected beam may be considered gaussian within the accuracy of the scan. Figures 8 and 9 are scans taken after 75 and 150 round trips, respectively. The 3-section line was about 400 m long. Consequently, after 150 round trips the light pulse had traveled 120 km and passed 900 lenses.

The slight tilt of the profile may be interpreted as light which accompanied the beam in higher order modes.[9] Many more scans were taken in this and longer lines for various numbers of round trips. Figures 7, 8, and 9 are representative of the results.

IV. DISCUSSION OF THE EXPERIMENT

A question that has to be investigated in more detail is whether a 120 km lens guide would actually cause the same negligible distortion on a light beam as found for the shuttle pulse experiment. There are three important points to be considered:

(*i*) The distortion added to the beam by the optical components other than the lenses.

(*ii*) The finite apertures of these components.

(*iii*) The periodic nature of a shuttle pulse experiment.

In the shuttle pulse line there were, in addition to the lenses under investigation, several other optical components, such as the switch,

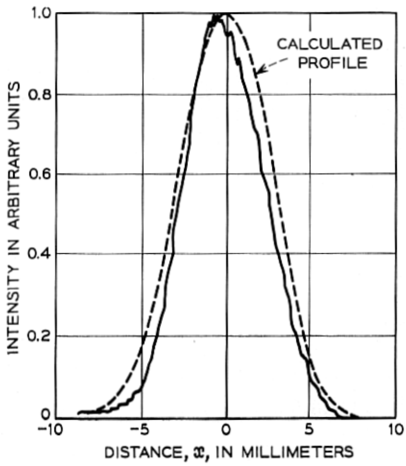

Fig. 8 — Intensity scan across the guide cross-section for light after 75 round trips in the 3-section line.

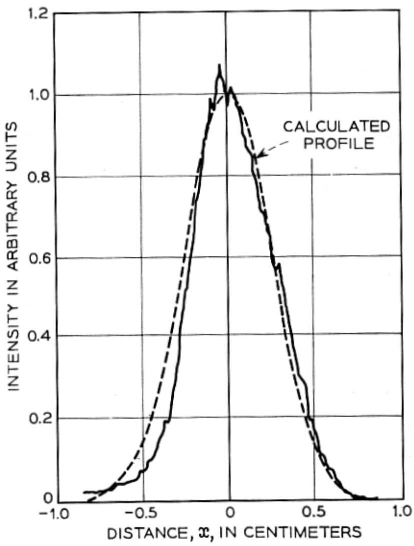

Fig. 9 — Intensity scan across the guide cross-section for light after 150 round trips in the 3-section guide.

the amplifier, and the telescope, which the light passed twice on every round trip. To find their contribution to the beam distortion, the nature of the expected irregularities on an optical surface has to be considered.

Any irregularity on an optical surface will distort the beam, but not all of this distortion will accumulate in a lens guide, because the finite aperture of the guide smooths out the intensity and phase-front of the beam. This is equivalent to saying that only low order modes will be transmitted in the guide. Consequently these modes are the only growing source of distortion. They are generated by irregularities correlated over areas comparable to the beam cross section: smooth bumps whose heights determine the amount of light coupled into these modes.[9]

The polishing process will normally cause those bumps to be the highest which extend furthest over the surface. Hence it is expected that a large beam will be distorted more than a small one. This implies that those optical components on which the beam had only a 1 mm diameter contributed very little to the distortion. So only the two large mirrors facing the line are left as major additional sources of beam distortion. Since they had the same optical quality and beam size as the lenses, their contribution may be considered approximately the same as an additional lens in the line.

The second point deals with the effective beam aperture of the shuttle pulse line. The amplifier had an inner diameter of 4 mm, and the KD*P crystal had a cross section of 3×3 mm. Both were in the 2 m section between the small telescope mirror and the end mirror. For a wavelength of 6328Å, an aperture of 3 mm, and a spacing of 2 m, one calculates an effective Fresnel number of 1.8. In this section the beam had the same shape and phase front as in the confocal 2 m oscillator cavity from which it was originally ejected.

Applying Slepian's propagation coefficients for modes in a diffraction-limited confocal cavity one finds, for a Fresnel number of 1.8, a diffraction loss of about 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3} per transit for the first, second, third, and fourth parasitic mode, respectively.[11] More significantly, all these modes except the fourth one went into oscillation in the 3-section line. Hence the aperturing in the system should not suppress the mode buildup for modes up to at least the third order.

Further investigation of the individual modes shows that the first and second parasitic modes are not only generated by irregularities on the lens surfaces, but also by additional lens effects, for example, in the gain medium of the amplifier tube or by lens displacements, laterally and along the axis. In turn these modes can be suppressed, even in a line with imperfect lenses, by proper alignment of these lenses.[8] This means that the first and second parasitic modes cannot be used to determine the lens imperfections in the experimental guide. They could be and were avoided by proper alignment.

Let us look therefore at higher modes, say, the third one. Figure 9 in Reference 9 shows the profile of a gaussian beam with 5 per cent of its power in the third mode. Comparing this with the recorded profile in Figure 8 one may assume that its distortion was of the same order. Without pushing the quantitative analysis of the experiment too much, it can be said that the power collected in the third mode after 900 lenses was apparently not larger than a few per cent of the beam power.

Gloge[9] predicts this amount (and only a fraction of this in the next higher modes) for the lenses used, if the irregularities on the surfaces are correlated over distances about twice the beam diameter. On the basis of these calculations it may be assumed that the detection of the higher order modes would be beyond the experimental accuracy.

The third point has to do with the iterative structure of the lens

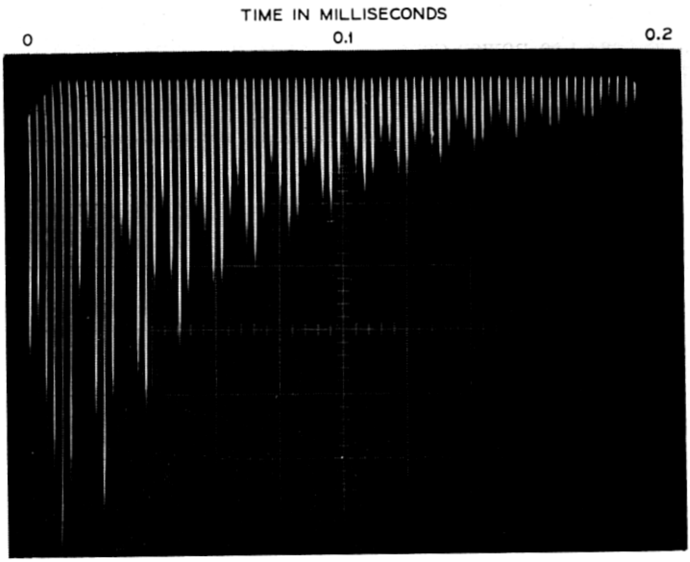

Fig. 10 — Pulse train from the 3-section line after one lens was misaligned.

guide simulated by the shuttle pulse line. Obviously on every round trip the light pulse suffers the same kind of distortion, whereas in a real lens guide this distortion would be completely at random.

Consider for example the most simple irregularity: a displaced lens. Figure 10 shows a pulse train similar to Figure 5 but after one lens was misaligned. Apart from the expected decay there is a periodic fluctuation of the signal. This can be explained by an oscillation of the beam center about its correct position or, which is equivalent, by periodically generated and annihilated parasitic modes. One can show that the modes, because they travel with a propagation constant slightly different from that of the gaussian beam, should do exactly that in a periodic structure.

Only if the round trip is an integral number of beat periods for a specific mode will the power in that mode grow continuously. To multiply the minute effects expected per section in the experiment this condition was arranged for the third order mode. This was done by changing the distance of the telescope mirrors and watching the periodic fluctuations of the pulse train. One can calculate that the third mode builds up if the fluctuation period is three pulses on the pulse train. In this case we should observe the maximum third order mode distortion of the beam. Scans taken under this condition indicated no major deviation from the scans shown. The explanation might be that the power generated per round trip in the third mode was smaller than, or at most, equal to the attenuation of that mode.

In a lens sequence with independent random irregularities, the relative phases are completely arbitrary and the average power in the parasitic modes would grow proportional to the number of lenses passed, at least as long as reconversion can be neglected. If, as an upper limit, the generation rate per round trip is assumed equal to the loss of 2×10^{-4}, the third mode would increase to 3 per cent of the beam intensity after 900 equivalent lenses.

V. CONCLUSIONS

A ½-mile underground lens guide with six confocally spaced lenses was investigated by sending a light pulse back and forth in this guide. The lateral intensity profile of the light beam could be checked after any round trip by scanning the intensity in the cross section. It was found that the gaussian profile after passing 900 lenses was still virtually undistorted.

The lenses had a quality of $\lambda/10$, a diameter of 60 mm, and were antireflection coated to give a reflection and absorption loss of one per cent per pass. The effective aperture of the guide was determined by an amplifier tube and an optical switch within the path of the light. The diffraction losses for modes up to at least third order were negligibly low. Even for the condition of critical buildup of the third mode the distortion of the light profile after 900 lenses was negligible.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. E. A. J. Marcatili for many fruitful discussions, and they gratefully acknowledge the constructive assistance of Mr. H. E. Earl.

APPENDIX

Assume that the peak pulse power entering through the switch is I_1 and that the pulse loses a fraction p of its intensity on every round trip. Consequently, after N round trips, the intensity

$$I_N = I_1 10^{N \log (1-p)} \tag{1}$$

is left in the pulse. At the same time a power I_s leaks in through the switch continuously and increases the background light I_b to a level, where I_s just replenishes the loss per round trip. If I_s adds in phase to the light already circulating, as in a perfect resonator, the comparison of amplitudes yields

$$\sqrt{I_b(1-p)} + \sqrt{I_s} = \sqrt{I_b}\ . \tag{2}$$

If the phases are completely at random because either the resonant frequency or the entering light frequency changes within the round trip time one has instead

$$I_b(1-p) + I_s = I_b\ . \tag{3}$$

By introducing a stability parameter $\alpha = 1$ or 2, both (2) and (3) can be expressed by the relation

$$I_b = I_s[1-(1-p)^{1/\alpha}]^{-\alpha} \tag{4}$$

which for $p \ll 1$ reduces to

$$I_b = I_s\left(\frac{p}{\alpha}\right)^{-\alpha}. \tag{5}$$

It is convenient to define a signal to noise ratio

$$R = 10 \log \frac{I_N}{I_b}$$

required at the receiver to analyze the Nth pulse and an extinction ratio

$$E = 10 \log \frac{I_1}{I_s}$$

inherent in the switch. By combining (1) and (5) and solving for N, one now finds the number of round trips which can be properly detected:

$$N = \frac{R - E - 10\alpha(\log p - \log \alpha)}{10 \log (1-p)}. \tag{6}$$

The derivative $\partial N/\partial p$ vanishes for

$$N = \alpha \frac{1 - p_{\text{opt}}}{p_{\text{opt}}}. \tag{7}$$

This is the maximum number of round trips that can be achieved with the optimum round-trip loss, for example by adjusting the amplifier gain. Equations (6) and (7) were used to plot Figure 6. It shows p_{opt} as a function of the difference $E - R$ for $\alpha = 1$ and 2.

These two lines present the limits of perfect resonance and completely random phase buildup. For example, to receive the 150th pulse 20 dB above the noise level in a line that does not resonate, one needs an extinction ratio of 46 dB in the switch and a loss of 0.67 per cent in the shuttle pulse line.

REFERENCES

1. Goubau, G. and Schwering, F., "On the Guided Propagation of Electromagnetic Wave Beams," Trans. IRE, *AP-9* (May 1961), p. 248.
2. Kompfner, R., "Optical Reflecting System for Redirection of Energy," U. S. Patent 3-224-330 issued December 21, 1965.
3. DeLange, O. E., "Losses Suffered by Coherent Light Redirected and Refocused in an Enclosed Medium," B.S.T.J., *44,* No. 2, (February 1965), pp. 283–302.
4. Goubau, G. and Christian, F. R., "Loss Measurements with a Beam Waveguide for Long Distance Transmission at Optical Frequencies," Proc. IEEE, *52* (December 1964), p. 1739.
5. Gloge, D., "Experiments With an Underground Lens Waveguide," B.S.T.J., *46,* No. 4, (April 1967), pp. 721–735.
6. Marcatili, E. A. J., "Ray Propagation in Beam Waveguides With Redirectors," B.S.T.J., *45,* No. 1, (January 1966), pp. 105–116.
7. Gloge, D., "The Effect of Density Fluctuations in a Gas Filled Undeground Optical Waveguide," Proc. Symp. Mod. Opt., Brooklyn Polytechnic Pren.
8. Marcatili, E. A. J., "Effect of Redirectors, Reforcussers and Mode Filter on Light Transmission Through Aberrated and Misaligned Lenses," B.S.T.J., *46,* No. 8, (October 1967), pp. 1733–1752.
9. Gloge, D., "Mode Conversion in an Underground Lens Guide," B.S.T.J., *46,* (December 1967), pp. 2467–2484.
10. Steier, W. H., "Coupling of High Peak Power Pulses from He–Ne Lasers," Proc. IEEE *54* (November 1966), pp. 1604–1606.
11. Slepian, D., "Some Asymptotic Expensions for Prolate Spheroidal Wave Functions," J. Math. Phys. *44* (1965), pp. 99–140.