Guidance of 100-GHz Beams by Cylindrical Mirrors

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Abstract—**Microwave beams can be kept confined by sequences of pairs of cylindrical mirrors, each pair acting as a lens. At 100 GHz, with 1.2-m × 1.2-m focusers spaced 80 m apart, a loss of the order of 2 dB/km has been measured in clear weather. The use of this beam-guiding arrangement, called a "Hertzian cable," for distribution of information in cities is discussed.**

I. INTRODUCTION

WE REPORT experiments that demonstrate the feasibility of high-capacity Hertzian cables to distribute and collect information within cities. By Hertzian cable we mean a succession of components capable of redirecting incident beams in any direction in space, focusing them with adjustable degrees of convergence and dropping channels in quasi-optical form [1]. The Hertzian cable scheme makes use of millimeter wave beams propagating through the atmosphere. There is therefore no need for digging trenches in the streets as is the case for conventional cables. The close confinement of the beams, insured by a system of refocusers located on roof tops, minimizes the diffraction losses and the interferences [1], [2]. It is also possible to circumvent obstacles, at the cost of a somewhat increased path length. The attenuation due to rain at frequencies above 100 GHz is rather high, of the order of 30 dB/km, for most populated regions and outages acceptable in communication. Yet this attenuation appears to be tolerable over distances not exceeding a few kilometers.

Christian and Goubau first demonstrated the possibility of guiding microwave beams over distances of a few meters with dielectric lenses [3]. The condition for the diffraction losses to remain small in such a system is that the lens area be large compared to the product of the wavelength and lens separation. For example, if the wavelength is 3 mm and the separation between adjacent lenses is 100 m (a distance that corresponds roughly to the separation between adjacent buildings in a city) the lens diameters should be of the order of 1 m. For the envisioned application, a pair of cylindrical mirrors turns out to be more practical than dielectric lenses, because mirrors are free of Fresnel reflection and because they can redirect outgoing beams in almost any direction in space, a feature which is required to circumvent obstacles. Furthermore, the effective focal length of a pair of cylindrical mirrors can be changed, either by changing the mirror curvature through mechanical deformation, or by changing the mirror orientations. In the first section of this paper, a few theoretical results applicable to the propagation of beams through pairs of cylindrical mirrors are recalled.

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II. THEORY OF BEAM REFLECTION ON CYLINDRICAL MIRRORS

It is well known that under reflection on a cylindrical mirror, collimated ray manifolds converge at distances $f = (\rho/2) \cos i, f' = (\rho/2)(\cos i)^{-1}$ from the mirror vertex, depending on whether the incidence plane is perpendicular or parallel to the mirror generatrix. (ρ denotes the mirror radius and i the incidence angle.) A combination of two cylindrical mirrors whose generatrices make an angle of 90° to one another therefore provides sharp focusing of incident ray pencils [1], provided their radii ρ_1, ρ_2 are such that $(\rho_1/2) \cos i = (\rho_2/2)(\cos i)^{-1}$. There are reasons, however, to choose more complicated orientations of the two mirrors than the one just described, and to let the mirror generatrices make angles close to 45° with respect to the incidence planes. In such an arrangement, better use is made of the available mirror area, and the deformation of the mirrors is minimized. Furthermore, the effective focal length of the system can be adjusted by changing the mirror orientation. The calculation of the system focal length is most easily made by considering the change in path length resulting from the mirror curvature and adding the contributions of the two mirrors. The effective optical thickness can be made the same as for a lens with rotational symmetry by a proper choice of the parameters [4]. Design values are given in Fig. 1 for beam deflection angles θ of 90°, 180°, 270°, and 0°. In Fig. 1 the angle $\Omega = 0°$, 180° is exemplified. In some cases it is useful to consider nonplanar paths, $\Omega \neq 0$, 180°. The angle ν denotes the angle that the mirror generatrices make with the incidence plane. The two mirrors are assumed to have the same radius of curvature ρ. The mirror deformation is smaller in the arrangement presently considered than in the orthogonal arrangement previously described. The maximum deformation of the mirrors is of the order of the wavelength (e.g., 3 mm) for confocal spacing. It therefore decreases as the frequency of operation is increased.

It turns out that within the approximation of Gauss, wave-optics effects can be readily evaluated, once the ray-optics properties of the system are known. If we assume that the beam launched into the system has a transverse irradiance distribution close to a Gaussian curve, the beam radius and wavefront curvature at the exit plane are given by the so-called "*ABCD*" law, which is essentially a geometrical optics law [5]. The theoretical

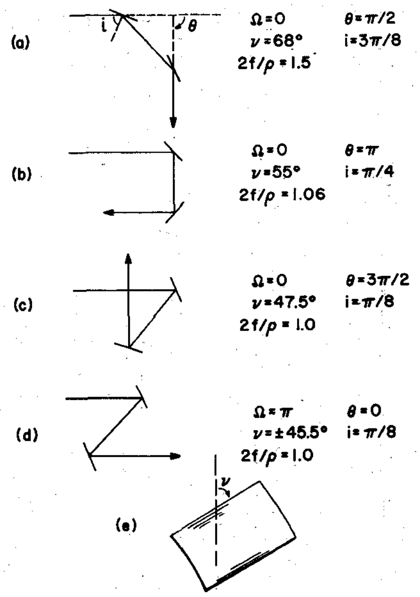


Fig. 1. Design values for beam deflection and focalization by pairs of cylindrical mirrors. ρ denotes the radius of curvature of both mirrors, f the effective focal length of the system, and Ω denotes the angle between the planes of incidence at the two mirrors.

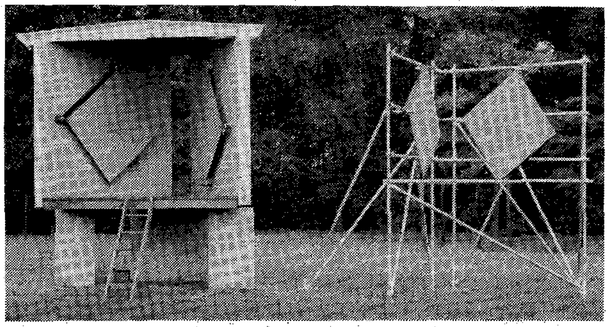
losses due to the mismatch between the transmitted beam and the beam accepted by the collector were found to agree closely with experiment [6]. It should be noted that, if the separation between the two mirrors of any given pair is not negligible compared with the focal length, the optical system should be considered a "nonorthogonal" quasi-optical waveguide, that is, a system lacking meridional planes of symmetry. Theoretical expressions for beam transmission and beam coupling in nonorthogonal systems have been obtained [4], [7].

III. BEAM LAUNCHER AND COLLECTOR

The beam launcher and the beam collector are of the periscopic type [8] and make use of 0.75-m parabolic dishes and dual-mode feeds. The field radiated by these antennas was found to have an almost Gaussian amplitude distribution with a radius ($1/e$ point of the irradiance) equal to 0.14 m. The convergence of the launched beam can be varied (within limits imposed by spherical aberration) by displacing the feed along the paraboloid axis.

IV. CYLINDRICAL MIRRORS

The mirrors first experimented were in aluminum [4]. Commercial glass mirrors were subsequently used because of their higher degree of flatness before bending. (As a result of technological difficulties in the use of glass mirrors the most recent tests were conducted with metallic mirrors.) The mirror size is 1.2 m × 1.2 m. The plate is bent to the appropriate radius of curvature by applying bending moments at the edges. For confocal spacing the maximum deformation of the mirrors is of the order of one wavelength, about 3 mm. These mirrors are used as



(a) (b)

Fig. 2. Photograph of the cylindrical mirrors mounted on (a) a wood protected structure and (b) a steel pipe unprotected structure. Alignment is provided by ball joint and thrust bearing arrangements at the two top corners of the mirrors, and a ball joint with shock absorbers at the middle lower part of the mirror.

front surface mirrors, the copper plating being protected by a thin dielectric layer which is transparent to millimeter waves (note that glass is essentially opaque to millimeter waves). The possibility of adjusting at will the mirror curvature turns out to be an important feature for minimizing the transmission losses. The structures used for supporting the mirrors are shown in Fig. 2.

V. EXPERIMENTAL SETUP

The path, set up at Crawford Hill, N. J., is shown in Fig. 3. It incorporates 20 mirrors and is 800 m long. The separation between adjacent focusers is 80 m. The lower curve in Fig. 4 gives the sum of the measured launcher and collector losses, (0.9 dB each) the measured losses due to two Mylar windows, and the absorption by the oxygen line of the atmosphere. The upper curve gives the total measured round-trip transmission loss of the system. We see that the contribution of the refocusers to the loss is only 1.6 to 3.2 dB from 98 to 109 GHz (that is, 0.16 to 0.32 dB/refocuser).[1] This loss is due mainly to wavefront distortion and spillover, the ohmic losses being almost negligible (0.01 dB/refocuser). This means that the loss could be reduced further, perhaps by a factor 10, if the mechanical accuracy were improved and the mirrors had slightly larger sizes. (The diffraction loss varies exponentially with the mirror size.) However, the loss that has been measured is already negligible compared with the attenuation expected from rain.

To determine the losses due to the mirror surfaces being wet, a mirror was thoroughly sprayed with water. The attenuation increased by 0.1 dB. Recovery occurs 30 s after the termination of the spraying under average wind conditions. The variations in transmission due to wind are of the order of 0.2 dB for 8–16 km/h winds and 0.5 dB for 24–32 km/h winds. Gusts of 55 km/h winds can produce up to 2-dB variations [9]. Slow daily varia-

[1] Even lower losses have recently been obtained with offset launchers and magnesium mirrors. The results will be reported shortly by I. Anderson and J. T. Ruscio, "105-GHz low-loss beam waveguide."

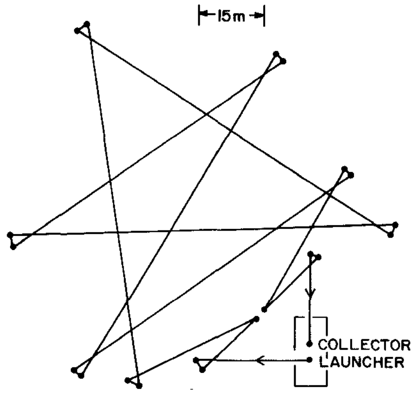


Fig. 3. An 800-m long experimental path. Each circle represents a mirror. The beam launcher and the beam collector are located in a common building, shown as a rectangle. The source is a swept backward wave oscillator.

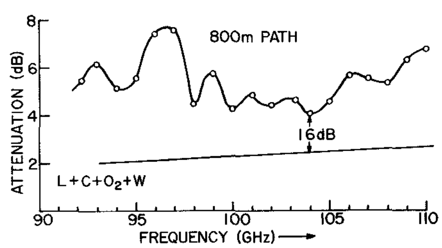


Fig. 4. Measured total round-trip attenuation as a function of frequency in clear weather (circles). The straight line corresponds to measured launcher, collector, window, and oxygen absorption losses.

tions, not exceeding 3 dB, have been observed; they are attributed to thermal changes resulting in deformations of the supporting structures made of steel pipes. (These last results were obtained with a 350 m long path.)

The results given above, when extrapolated to a 2-km path with a 100-m refocuser separation indicate that the loss in clear weather from the source (perhaps, an IMPATT diode) to the detector, would not exceed 15 dB in the 100–110-GHz band. Hopefully, no active alignment would be required. Recent measurements [10] have shown that in many cities (such as London) the loss due to rain does not exceed 22 dB for a 2-km path 99.99 percent of the time in that frequency band. The outage would be larger in New Jersey for the same attenuation [11], [12]. A total loss of 37 dB (15 dB + 22 dB) is quite tolerable even for large-capacity systems.

Fig. 5 is a view of how the system would look in a city. At some locations, spectral components of the beam would be dropped for local use with the help of quasi-optical filters, essentially large area Fabry–Perot resonators [13].

In conclusion, the Hertzian cable concept appears to be technically feasible in the 100–300-GHz frequency range. Further investigation is needed concerning the long-term operation of the system and the channel-dropping filter technology. This system is attractive mainly as a very high-capacity system with many different paths crisscrossing densely populated cities. It is not known at the moment whether the Hertzian cable system

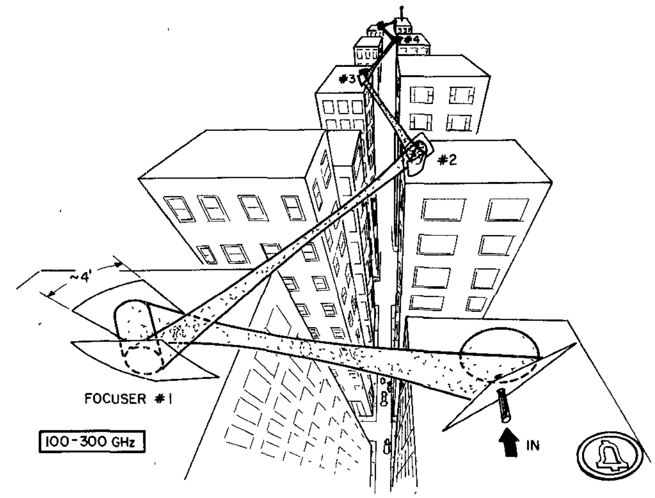


Fig. 5. Possible arrangement in a city. Pairs of cylindrical mirrors are located on roof tops for redirection and refocusing. Channels could be dropped with the help of quasi-optical filters (not shown on the figure).

can compete with more conventional radio systems when interference is not a fundamental limitation.

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