The background of the page is a repeating pattern of a sphere array, consisting of vertical stems with spheres at the top, rendered in a light, semi-transparent grey. The title is centered over this pattern.

# MICROWAVES and SOUND



*A sphere array can simulate an isotropic dielectric since it can be made to have 3-dimensional symmetry.*

Winston E. Kock

A recent development shows that obstacle arrays, modeled after the periodic structure of crystals, refract and focus not only electromagnetic waves, but sound waves as well.

The use of lenses to focus waves other than those of light is not new, either in the field of acoustics or that of radio. Indeed, many physics students must have seen demonstrations of the bending of sound waves by a prism of carbon dioxide confined within a membrane. Hertz himself used prisms of pitch to bend the short radio waves with which he worked in demonstrating the like nature of light and of the electromagnetic radiation predicted by Maxwell. These were laboratory experiments, however, and it was not until lenses were used in connection with microwave antennas during and after the war that the full potentialities of the dioptrics of microwaves, and later, of sound, became apparent.

It may seem fortuitous that devices designed for electromagnetic radiation can be used with sound waves, a very different type of wave, and conversely, that experiments with sound waves can help in the understanding of the electromagnetic radiation known as microwaves. Actually this can be because the length of sound waves and the length of microwaves are comparable. A medium with which acoustic radiation can interact mechanically and a microwave radiation electromagnetically, provides the means for making a comparison.

#### Continuous vs Discrete Dielectrics

To make the small lenses with which one focuses light one uses a smooth dielectric substance such as glass. By smooth is meant a medium whose structure is uniform and small compared with the wavelength of radiation passing through it. Max Born, in his book *Optik*, presents an elegant proof that the equations which describe the behavior of electromagnetic waves in such a continuous medium can be arrived



*The waveguide type artificial lens must be concave to be convex (converging) because its refractive index is less than unity.*

at by assuming the medium to be an assemblage of discrete re-radiating particles.

As an electromagnetic wave passes through such an assemblage, the charges it induces on the particles regularly re-radiate energy which adds to or subtracts from the wave itself. If there are many particles per wavelength, the re-radiated energy combines with that of the wave which excites it so smoothly that the wave merely suffers an alteration in velocity.

For light, for which the wavelengths are so short, particles of molecular dimensions are required for such behavior; but for microwaves, because the particles could be shaped and sized without much difficulty, one could construct such an assemblage. We all know that transparent crystals are actually regu-

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lar arrays of molecules. Glass is not composed of a regular array of molecules, but if the arrangement is uniform in density and composition, refraction of light will take place if there are many molecules per wavelength. If there are only a few particles per wavelength, as in artificial dielectrics for microwaves, then the regularity is more important; the assemblage is therefore made analogous to the periodic structure of crystals.

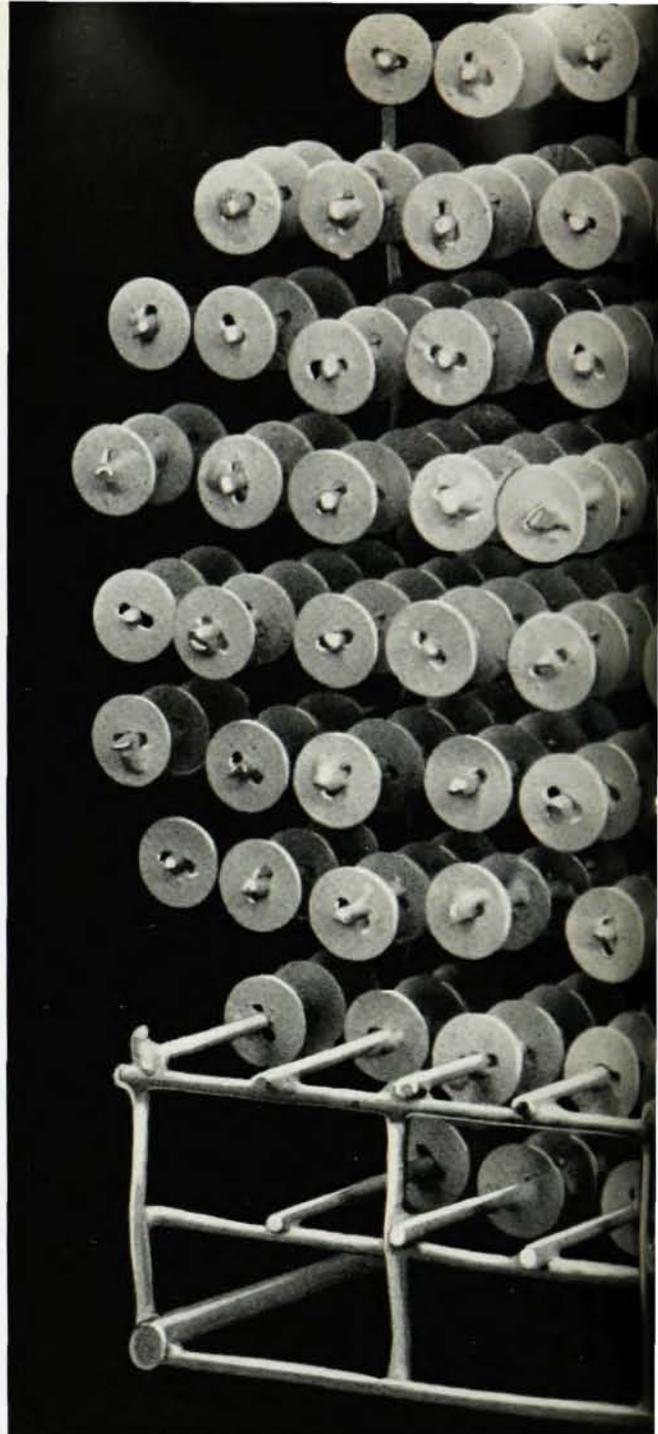
For microwaves, the re-radiating particles could be of metal on which currents would be induced by the incident wave and the moving charges regarded as a new source. In the analogous case of sound, the rigid, immovable particle would reflect and radiate energy from the incident sound wave and again it could be looked upon as a new source. The "smooth" dielectrics of microwave lenses, then, need not be smooth to the light which gives us our sight, but only to the grosser radiation which they are designed to focus.

### The Waveguide Microwave Lens

The figure on the preceding page shows the first practical type of obstacle lens, developed during the war. It used thin electrically conducting plates, parallel to each other, edge on to the direction of propagation of the wave, and parallel to the electric vector of the radiation to "short circuit" it.

This lens was arrived at not by analogy with the structure of a crystal, but as a derivative of the waveguide used in microwaves. In fact it may be thought of as made up of a lot of rectangular waveguides with the top and bottom walls removed, leaving only the side walls. As in the case of a waveguide, the phase velocity of the wave is greater than the velocity in free space. A convex lens would be a diverging lens, and in order to make a lens converging, or positive, it must be made concave, as is the lens in the figure.

This waveguide type of artificial dielectric has certain well known optical properties in a very exaggerated degree. It is strongly double-refracting. For radiation with the electric vector normal to the metal sheets the dielectric constant is substantially unity. Like the waveguide from which it was derived, this dielectric has a lower cutoff frequency. For frequencies below this it is opaque to electromagnetic radiation and reflects rather than transmits. Just above this frequency the refractive index is less than unity and it increases very rapidly with

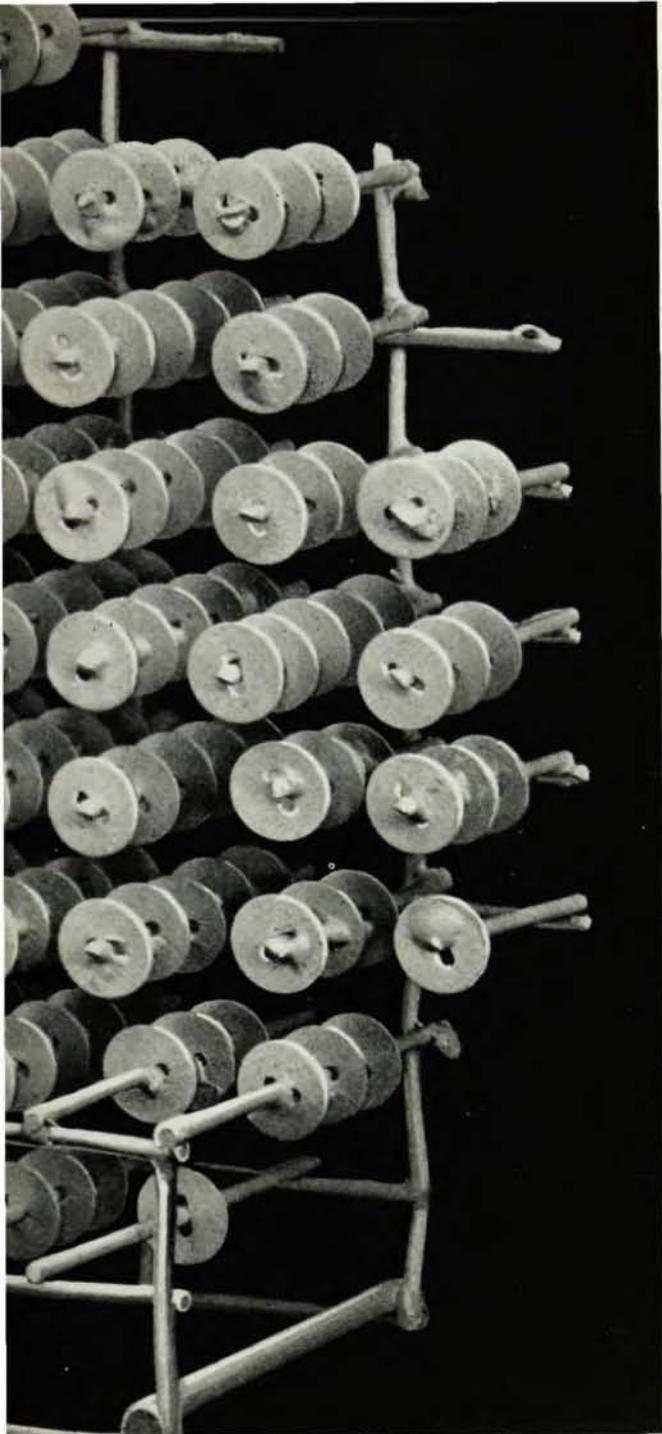


frequency. In optical terms, the dielectric exhibits anomalous dispersion.

### The Obstacle Type

The waveguide type of dielectric is suitable only when the band of frequencies to be transmitted is rather narrow. In further advances in the microwave art, it became desirable to make artificial dielectrics whose indices of refraction varied less rap-

*For wavelengths which are long compared to the disk diameter, this lens-shaped array of rigid, electrically conducting obstacles will focus either electromagnetic waves or sound waves.*



idly with wavelength or with frequency. In optics one deals usually with substances which have a dielectric constant greater than unity and one which varies rather slowly with frequency. Might it not be possible to simulate this behavior artificially?

A natural dielectric substance behaves as it does because it is composed of discrete particles which are excited by the electromagnetic waves. We might expect, as reasoned in the introduction, that the be-

havior of natural dielectrics would be simulated by an array of conducting particles on a scale very large, of course, compared with that in a natural dielectric, but still small compared with the wavelength of the radiation to be used. This turns out to be true. Conducting spheres, disks, or strips can be used. The lens in the second figure has as a dielectric an array of disks. As expected, it is found that in these obstacle arrays the phase velocity is less than that of light and the index of refraction is fairly constant for all wavelengths long compared with the size and spacing of the elements.

We can now compare the two sorts of artificial dielectric with that of a natural refracting medium, and this is done in the curves of the figure on the following page. The dependence of refractive index on frequency for the waveguide dielectric (left) resembles that of a natural dielectric (center) at A, while that of the array of obstacles reproduces the more desirable portion BB of the center curve.

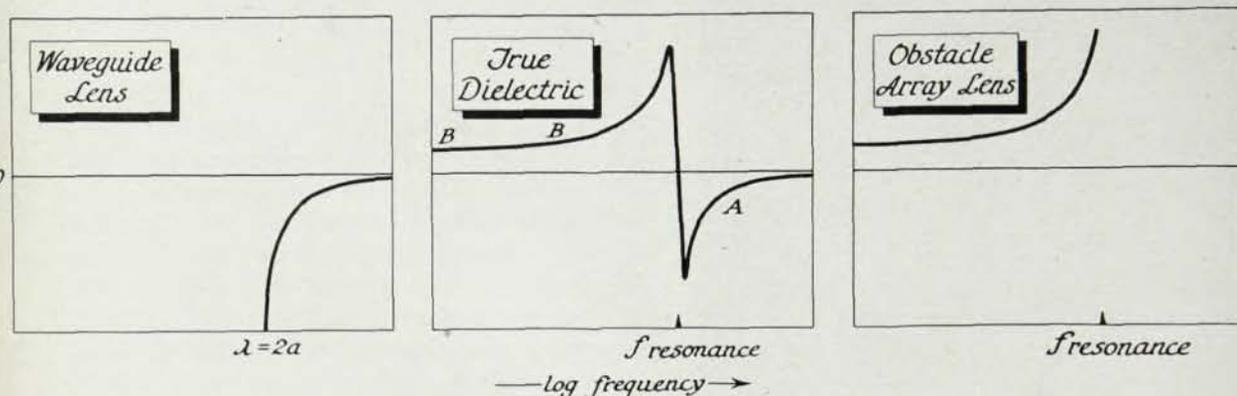
Once the general nature of artificial dielectrics and the relation of their behavior to that of natural dielectrics has been understood, it is possible to design into the artificial media the properties we observe in natural dielectrics. Spheres arranged in a cubic array exhibit a refractive index which is independent of the polarization or direction of the electromagnetic wave; they thus reproduce an isotropic dielectric. On the other hand, conducting ellipsoids arranged in a cubic array display three different values of refractive index for waves polarized parallel to the three axes of the ellipsoids. Such arrays correspond to anisotropic dielectrics and cause double refraction (birefringence) of waves having components polarized parallel to two of the axes of the ellipsoids.

Birefringence is also exhibited by arrays of spheres having unlike spacings in the three coordinate directions. Similar rectangular arrays of ellipsoids can be made to appear isotropic at low frequencies and yet will show birefringence as the resonant frequency of the ellipsoid is approached. Extreme birefringence is displayed by arrays of strips. Waves polarized parallel to the strip length are reflected (infinite dielectric constant), waves traveling in a direction parallel to the strip length have unchanged

velocity (unity dielectric constant), and waves whose electric vector lies in the plane of the strips and is perpendicular to their length have a velocity less than the free space velocity (intermediate dielectric constant).

Arrays of short rods affect only those wave components which have their electric vector parallel to the rods, and consequently such arrays furnish a simple structure for reproducing the half-wave and quarter-wave plates of optics. Linearly polarized microwaves passing through an array of rods oriented at 45 degrees to the electric vector will, with

flected before transmission again takes place. For more widely spaced arrays, on the other hand, transmission at the higher phase velocity where the index of refraction is less than unity occurs even before resonance of the elements has been reached. This is because the array reverts to the waveguide lens structure when the transverse spacing between elements exceeds one-half wavelength, and the waveguide mode can propagate between the elements. Similarly, a low frequency pass band can be attributed to the waveguide structure, since at very long wavelengths even the large plates become small com-



*The dependence of refractive index on frequency*

the proper array thickness, undergo a 90-degree rotation of their plane of polarization. Thinner arrays will transform such waves into circularly or elliptically polarized waves.

It might be expected that the curve of index of refraction versus frequency of the sphere and disk arrays would continue to follow that of a natural dielectric at frequencies higher than the resonant frequency (dipole resonance) of the elements. This does indeed occur for small element densities. For closely packed arrays, however, there is a band of frequencies over which the waves are totally re-

pared to the wavelength and therefore act as transparent delay elements.

### The Sound Lens

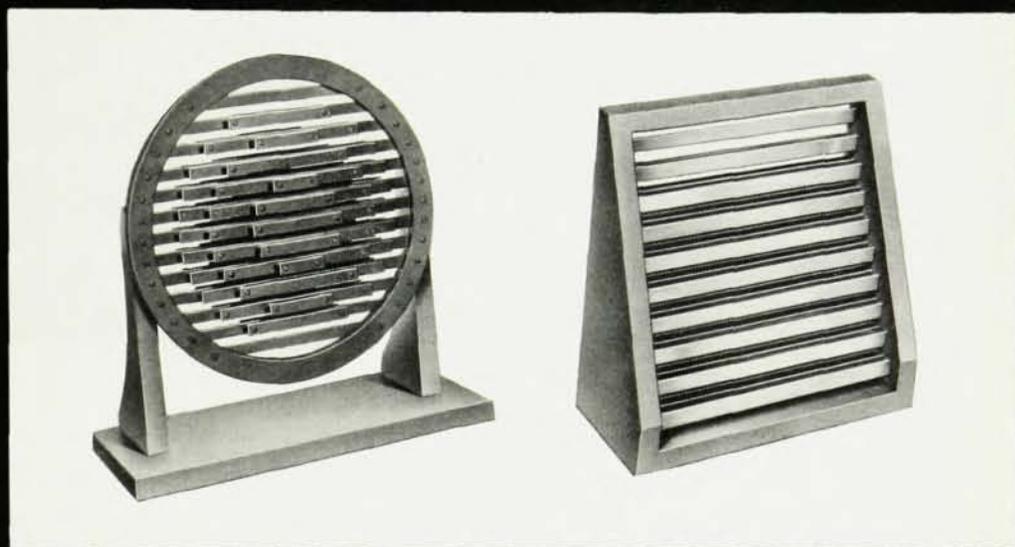
It was Lord Rayleigh who first, in connection with his studies of sound, described the transmission of electromagnetic waves through pipes which we now call waveguides. In his paper, *On the Passage of Waves Through Apertures in Plane Screens and Allied Problems* (Collected Papers, Volume 4), he begins with the sentence: "The waves contemplated may be either aerial waves of condensation and rare-

faction, or electrical waves propagated in a dielectric." Further, he observes that in certain problems of passage through a slit and reflection from a blade, the same results are obtained for sound waves or electric waves if the blade (screen) is rigid, or perfectly conducting, respectively.

Since the elements of many of the microwave models are both rigid and electrically conducting, they refract both sound waves and electric waves. The mechanism of acoustic refraction is again explained by the re-radiation of energy from the obstacles. In this case the spheres or disks become,

wavelength for acoustic as for electromagnetic waves when the index is plotted versus wavelength (instead of versus frequency). The frequencies are of course vastly different. Oddly enough, it was not until after acoustic measurements had been made on a particular strip prism that certain of its unexplained electromagnetic properties were understood. This incident suggests the possibility of learning more about the behavior of natural periodic structures by means of simple acoustic or microwave experiments made on models.

Meanwhile, these lenses have important technical



*Electromagnetic or acoustic lens*

*A highly anisotropic refractor shaped as a prism and employing strips as obstacles. The dielectric constant can be infinite, unity, or variable, depending upon the polarization and direction of propagation of the electromagnetic waves*

under the influence of the impressed sound waves, small acoustic dipoles, and the resultant of the original wave and the re-radiated waves manifests itself as a new wave having a lower velocity in the medium. Needless to say, the waveguide type lens is not effective for sound waves because its operation depends upon the transverse nature of electromagnetic waves.

Because the resonant wavelength of a strip obstacle is a function of its width dimension, prisms or other refractors employing strips as the element exhibit the same variation of refractive index with

uses. For electromagnetic waves they provide certain advantages as microwave antennas and are in use in the radio relay television circuits of the Bell System. In acoustic applications, divergent lenses furnish a method for eliminating the objectional beaming effect of the high frequencies along the axis of a loud speaker. Their broadband properties are particularly useful here, where the refractive index must remain constant over the entire audio-frequency spectrum of many octaves up to 15,000 cycles.