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IMPROVED COUPLING TO INFRARED WHISKER DIODES BY USE OF ANTENNA THEORY

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It is shown that the dependence of the output of a whisker diode on its orientation in the polarized beam of an infrared laser can be explained on the basis of simple long-wire antenna theory. Outstanding improvements in coupling the diode to the radiation field can result when this fact is utilized in applications.

In the measurements of the frequencies of the H_2O and CO_2 lasers by harmonic mixing on a cat-whisker diode,[1,2] success was achieved only when several factors were simultaneously optimized. One of these was the coupling of the radiation fields to the diode structure, a fine pointed wire (whisker) in feeble contact with a polished metal or semiconductor surface, the criterion being maximum rectified signal from the diode. One can imagine two parts to the signal-production process; (1) currents are induced in (or on) the wire; (2) the currents are carried to the point contact and rectified there. This paper will be concerned only with (1). The fact that workable whiskers are many wavelengths long at these frequencies suggests that long-wire antenna theory might apply to them, and this is indeed true. In essence, the diode behaves as an antenna-receiver combination, with the whisker playing the role of a highly directional antenna.

The diodes used in the antenna pattern determinations consisted of 1 mil (25 μm) tungsten wire pointed by the standard KOH etching technique[3] and placed in contact with a silicon crystal wafer taken from a commercial run-in detector.[4] The radiation field was provided by an HCN laser ($P \approx 5$ mW, $\nu = 890$ GHz, $\lambda = 337\ \mu$m). The diodes used in the frequency measurements,[1,2] on the other hand, were made with finer tungsten wire (0.2–0.5 mil) in contact with a polished nickel surface and were operated at frequencies up to 28 THz. However, our experience showed that these latter diodes had similar antenna characteristics, so that we could exploit the greater ruggedness and larger signals of the former diode-frequency combination to obtain data applicable to both.

Figure 1 shows the geometry of the experiment. In assembling the diode, a length of tungsten wire is first pressed over a 10-mil wire to make the kink shown, which acts as a spring against the contact pressure, and is then inserted into a 5-mil hole drilled transversely in a length of stainless steel capillary tubing. The capillary tubing is then squeezed tightly onto the wire and soldered into a 1/16-in. brass rod. An alternative construction was to insert the wire (without a kink) axially into the capillary and then bend the wire at right angles; the upright portion of the wire acts as a spring in this case. The silicon wafer, 6 mil thick and 20 mil in diameter, is soldered to another support fashioned from 1/16-in. brass rod. This support is shaped as shown in order to eliminate interference effects that distort the antenna pattern.

Whisker and crystal supports are mounted in the open on a turntable that has a protractor for measuring the angle θ. The axis of rotation passes through the center of the whisker. The whisker position is fixed, whereas the crystal can be moved toward the whisker by a differential screw for contact adjustment. Electrically, the whisker is connected to the mount and the outer conductor of a coaxial cable, and the crystal is insulated from the mount and connected to the inner conductor. The dc output of the diode, which under HCN radiation is always such that the whisker is positive relative to the crystal, is amplified and applied to the y axis of an X-Y recorder; the x axis is synchronized with turntable rotation by means of a potentiometer driven by the outer rim of the protractor.

The output beam of the laser was collimated by lenses to a bundle of approximately parallel rays 10 mm in diameter, and the axis of rotation of the mount was adjusted to be in the center of this bundle. The true far-field pattern of the antenna is thus more closely approximated than by focusing the radiation onto the diode, although only about one-tenth the output is obtained. Focusing shifts and diffuses the pattern slightly.

As the turntable is rotated (manually), the response of the diode is automatically traced out on the X-Y recorder. Figure 2 is an example of such a trace. In this case, seven maxima are seen between $\theta = 0°$ and $90°$, with the strongest maximum closest to the wire at $\theta_{m1} \approx 18°$. The minima are very deep, practically nulls. Note that there is a null at 90°, that is, with the beam perpendicular to the whisker and $\vec{E}$ parallel to it. This is the customary orientation employed in commercial run-in detectors, where the whisker is across the narrow dimension of a waveguide. The pattern is symmetrical about 0°, and there are an equal

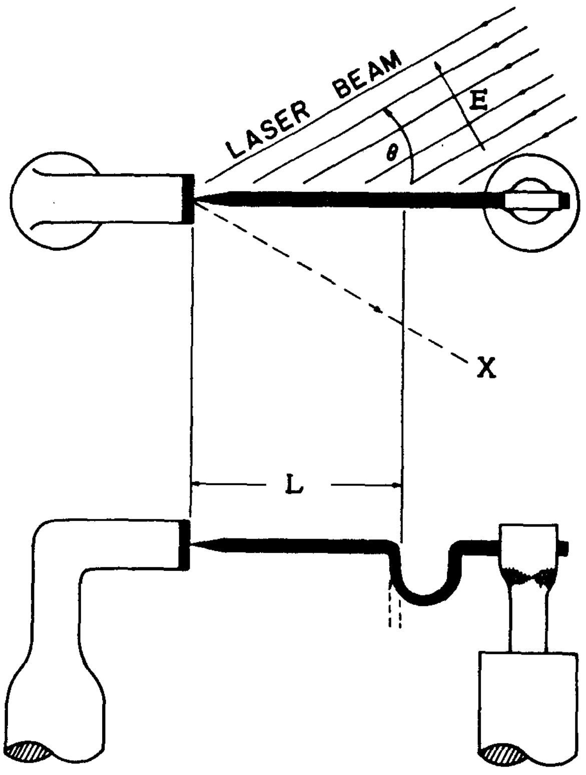

FIG. 1. Whisker diode geometry (not to scale). Top view is in plane of polarization of the laser beam. Dashed lines in lower view are for alternate whisker construction (see text). X marks possible location of re-reflector.

number of maxima beyond 90°, but they continually diminish in size.

As the whisker is gradually shortened by etching away a few mils at a time, the number of lobes in the pattern gradually decreases, and θ_{m1} increases. The diode output for the example of Fig. 2 was about 25 mV at the first maximum. As the whisker was shortened, this output varied, but the changes could not be correlated with the changes in length because of uncontrollable variations in the responsivity of the contact itself.

When $\vec{E}$ is parallel to the axis of rotation but everything else is the same, very little signal is picked up by the whisker. The antenna pattern is produced only when the whisker, $\vec{E}$, and the Poynting vector are in the same plane. This means the lobes are concentric circular cones about the whisker as axis.

The diode output can be approximately doubled by placing a mirror at the same angle as the radiation, but in the opposite part of the conical lobe, to re-reflect some of the scattered radiation onto the whisker. With a focused beam, a concave mirror of $R = 3$ cm in approximately concentric geometry with respect to the point contact works very well.

The theory of the long-wire antenna is well developed[5,6] and adequately fits straight conductors from one to many wavelengths long and up to half a wavelength thick. According to theory, each lobe in the pattern is a cone centered on the wire, and there is one lobe for each half-wavelength of wire length. Half of these lobes are tilted forward ($\theta = 0°-90°$) and half backward ($\theta = 90°-180°$). Thus the electrical length of the whisker antenna whose pattern is given in Fig. 2 is $7\lambda = 7 \times 0.337 = 2.359$ mm, since there are exactly seven lobes in the first quadrant. If the whisker is shortened to $6\frac{1}{2}\lambda$, the odd lobe appears perpendicular to it as a maximum at $\theta = 90°$.

In theory, the current distribution on a wire may be either progressive (traveling wave) or stationary (standing wave). The radiation pattern of the latter type has a plane of symmetry at $\theta = 90°$, whereas that of the former, like our whisker patterns, does not. The calculated ideal traveling-wave radiation pattern[5] for $L = 7\lambda$ is shown in Fig. 2, superposed on the experimental trace. In theory, deviations from the idealized distribution change the relative lobe amplitudes and fill in the nulls, but do not affect the angles of maxima and minima. The observed angles fit the theory as well as we could maintain good geometry (to better than 3° usually), but the relative lobe amplitudes and depth of minima did vary somewhat with different contacts. The contact is actually the "receiver" connected to the antenna terminals and so presents a certain load to the antenna. As the load impedance varies with the nature of the contact, the impedance match will vary and the resultant reflections and re-radiation by the antenna are bound to influence the measured pattern. Attenuation, by itself, evidently does not explain the differences observed here; its effect is to weaken the forward lobes relative to the ones farther back,[7] which is just the opposite of the effect seen in Fig. 2.

The formula for the angle of the first (greatest) maximum is[5]

$$\theta_{m1} = \cos^{-1}(1 - 0.371/L\lambda^{-1}), \qquad (1)$$

which shows that the longer the wire, the closer is the first maximum to the axis of the wire. We have found Eq. (1) to be very accurate in all of our experience which involved not only varying L from $\frac{1}{2}\lambda$ to 11λ for a fixed $\lambda = 337\ \mu$m, but also using the same L before different lasers with progressively shorter λ down to $\lambda = 3.39\ \mu$m. For example, a whisker with $L = 1.5$ mm has its first maximum at $\theta = 23°$ in HCN laser radiation ($\lambda = 337\ \mu$m) and $\theta = 4°$ in CO_2 laser radiation ($\lambda = 10.6\ \mu$m).

Where is L measured? Take the antenna of Fig. 2 as an example. Here the electrical length L is 7λ, as we have said before. The *physical* dimen-

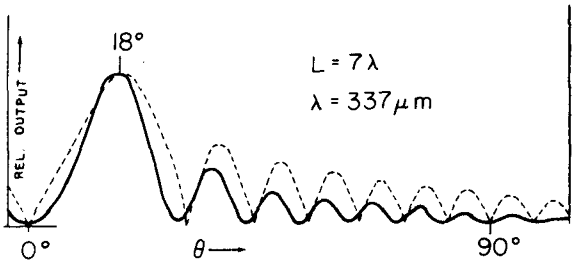

FIG. 2. Portion of the antenna pattern of a whisker seven wavelengths long. Solid curve, experimental; dashed curve, theoretical.

sion L, measured as shown in Fig. 1, was, for this case, equal to 7λ to within 0.1%. It is as if the remainder of the structure, i.e., the kink and beyond (or the right-angled bend in the case of kinkless whiskers), were not there at all. We obtained further proof of this by trying a whisker of the same total length from crystal to whisker support but with the kink very close to the contact. When the physical length L was about $\frac{1}{2}\lambda(\lambda = 337$ μm), the (single) maximum was found at $\theta \approx 70°$, which according to Eq. (1) corresponds to $L \approx 0.6\lambda$. The whisker was then etched down to $L \approx 3\lambda/8$, and this time there was a broad single maximum at 90° [Eq. (1) predicts 89.7° for this L]. The same whisker has a length $L \approx 4.5\lambda$ for $\lambda = 28$ μm. In radiation of this wavelength (H_2O laser), the first maximum was found at 23.5°, just as predicted by Eq. (1). At $\lambda = 3.39$ μm this lobe is expected at 8°; it was observed at about 10°.

The familiar rhombic and V antennas of radio practice are combinations of long-wire antennas. They achieve added gain and directivity by combining the first maxima of two or more long-wire antennas suitably arranged with respect to each other. An interesting application of this principle is the crossed-wire detector, in which a 2-mil phosphor bronze wire replaces the crystal in the mount. It is angled outward toward the tungsten whisker, the point of which rests lightly on the phosphor bronze wire. Contact pressure is adjusted in the same way as with a crystal. The two wires form a 50° V, with the opening toward the (focused) laser beam; the vertex of the V is the rectifying contact, and the legs are 6.75 and 10λ long. As with the tungsten-silicon diode, part of the structure has no effect, in this case, the wire behind the vertex. The responsivity of this device was poor (60 μV maximum in the HCN beam), but the maxima and minima were within a few degrees of the positions predicted for V antennas,[5] and the lobes were very sharp (2° wide).

These experiments show that the infrared cat-whisker diode behaves like a traveling-wave long-wire antenna, as far as its coupling to the radiation field is concerned, even at 88 THz (3.39 μm), where the whiskers are frequently thicker than the wavelength. The realization of this fact can be of much benefit in the utilization of these and like devices, e.g., Josephson junctions of the point-contact type.[8] The variation of the directional properties with frequency, the flexibility of the open structure, and the possibility of using re-reflectors to enhance output can all be exploited in applications. For example, in our frequency measurements,[1,2] it turned out that the separate laser beams could be brought into the antenna at close to the optimum angles for each. The K-band radiation was introduced at $\theta = 90°$, the whisker length being less than 0.1λ at this frequency. The openness of the structure made it possible to arrange these sources with a minimum of spatial interference.

Since simple antenna theory has worked this far, it is engaging to speculate that other types of antenna, e.g., the biconical antenna, which is many wavelengths transversely, can be used with the point-contact "receiver" at the frequencies above 28 THz. There is the possibility, too, of constructing narrow-beam devices (like the crossed-wire detector) for certain special applications.

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