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Wire-Grid Waveguide Bolometers for Multimode Power Measurement

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Abstract—**A grid of many fine wires connected in parallel, which completely fills the waveguide cross section, is shown to be useful as a multimode waveguide bolometer. Two such grids with wires that are perpendicular to each other are capable of sampling the power in all modes of propagation below some upper frequency limit determined by the wire spacing. In one case the "wires" consisted of metallized glass fibers, and in a second case they consisted of Wollaston wire wrapped tround supporting glass fibers. The wire-grid configuration which evolved from the thin-film bolometer of the same effective area is more stable and reproducible than the latter.**

Background

CONVENTIONAL methods of measuring the harmonic output of high-power microwave transmitters require that the magnetic or electric field near the waveguide walls be sampled at many points [1]–[5]. These methods are cumbersome and inaccurate when applied to measuring the higher frequency ranges, i.e., those that include very high harmonics of the fundamental power. They are cumbersome because the number of probes required are proportional to the number of possible waveguide modes, which in turn depend on the order of the highest harmonic present. They are inaccurate because quasi-optical modes, unlike normal waveguide modes whose power content can be measured by their surface fields, can exist in highly over-moded waveguide. By way of contrast, a thin-film bolometer can sample the total power flowing through a waveguide cross section [6], [7]. Also, a thin-film bolometer is much simpler in concept and implementation.

In an earlier study [7], [8] thin-film bolometers have been shown to be useful for the measurement of total integrated power. These bolometers are not limited with respect to frequency in the microwave and millimeter wave region. Neither do they discriminate between different modes of propagation to any significant degree. When more than one mode is present space harmonics will exist, however, the nulls produced by combinations of many modes are considered to be randomly disposed both in the transverse and longitudinal dimensions. The total power flow is then proportional to the sum of the integrals of the squared E- and H-fields taken over a cross section.

Earlier investigations by others [9]–[15] of thin-film bolometers for use in waveguide have been limited, for the most part, to measuring the fundamental power. The broadband capabilities of thin-film bolometers have been known [12], [16], and [17], but multimode operation with which we are here concerned has only been suggested [6]. This experimental study of multimode bolometers has been broadened to include new configurations of multimode wire bolometers that are superior in some respects to thin-film bolometers.

Wire-Grid Bolometers

Wire bolometers for microwave power measurement usually consist of a short length of fine platinum wire matched to a coaxial line or a ridged waveguide. Although such short lengths of fine wire may have broadband capabilities they are only suitable for measuring power in the fundamental or dominant mode.[1] Since the wire element is more stable and reproducible than deposited thin film, a means was sought for combining the stability of the wire bolometer with the broadband, multimode capabilities of the thin-film bolometer. It was reasoned that by quantizing the distributed surface resistance of the thin-film bolometer one could substitute wires for the resistive film. This, naturally, results in a grid of parallel wire resistors arrayed in a plane normal to the waveguide axis (see Fig. 1).

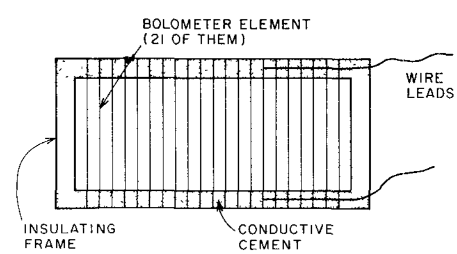

Fig. 1. Wire-grid bolometer for S-band and higher frequencies.

The spacing between neighboring wires must be no greater than a quarter wavelength at the highest harmonic frequency, and the wire diameter must be less than a skin depth. Also, the total resistance of all wires in parallel should equal the resistance of the equivalent thin-film bolometer. For maximum power absorption by a single bolometer terminated by a matched load the total bolometer resistance in rectangular waveguide with a cross section ratio of 2-to-1 should then be about 100 ohms between broad walls. This figure is predicated

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[1] While ridge waveguide can be made very broadband, the associated tapered mode transducer is designed for the TE_{10} mode only and will reflect most other modes.

upon a bolometer resistance equal to one-quarter the free-space-wave impedance, $\eta = 377$ ohms. The factor one-quarter consists of a factor of one-half for the 2-to-1 ratio of the dimensions of the waveguide cross-section and a second factor of one-half for the condition that there be maximum power transfer from the effective source impedance which here consists of the actual source impedance in parallel with a matched load. (This latter condition may not always be specified, of course, and a better-matched bolometer, i.e., better than the 3-to-1 VSWR that results here and consequently a less sensitive one, may be preferred.) For the case of the grid wire parallel to the broad walls the bolometer resistance, by the same token, should be four times as great, or about 400 ohms, while square grids should have a resistance of about 200 ohms.

Two types of multimode wire-grid bolometers were constructed for S-band and tested. In the first case the "wires" consisted of glass fibers on which was deposited a coating of gold and in the second case the wires were of the Wollaston type. The latter are extremely fine platinum wires used in commercial microwave bolometers. Wollaston wire is supplied with a supporting sheath of silver surrounding the platinum. After the wires are fixed in place the silver sheath is etched away leaving exposed a length of bare platinum wire invisible to the unaided eye.

Tests were performed on both types of multimode wire-grid bolometers. Several Wollaston wire-grid bolometers of various shapes were constructed including two orthogonally disposed square grids for sampling the total power passing through a square waveguide.

The metal-coated glass-fiber "wire"-grid bolometers were constructed to test the basic idea of the wire-grid bolometer pending receipt of Wollaston wire. It was also hoped that the relatively heavy film on the glass fibers, compared to the thin one on a thin-film bolometer, would have properties of the bulk metal, i.e., be more stable, but the metal-coated glass-fiber wire-grid bolometers also proved unstable with respect to resistance change with time. The glass fibers were about 0.004 inch in diameter. Conductive cement was used to secure the wire leads as well as the glass fibers and to provide two conductive strips. A gold film was then deposited on the glass fibers from one side using vacuum techniques until the desired resistance was obtained. The arrangement of the "wires" in Fig. 1 allows the bolometer to absorb power from all modes of propagation that have an E-field component parallel to the wires. This includes all modes except TE_{0n} modes. The arrangement in Fig. 2 allows the bolometer to absorb power from all modes except TE_{m0} modes. Therefore, both bolometers used together sample power in all possible waveguide modes. The grid spacing of about $\frac{1}{8}$ in. was the same for both bolometers. Special mounts were constructed for insertion between neighboring flanges in S-band waveguide. Bolometers with the two different wire orientations were tested with only one bolometer at a time in the waveguide, and with both bolometers in the waveguide; in some cases the bolometers were closely spaced and in some cases widely separated. No significant difference in performance was observed between the bolometers with metallized glass fibers and the thin-film bolometers designed for the same (S-band) waveguide. The bases of comparison are the apparent efficiency and stability. Apparent efficiency is here defined as the ratio of the power absorbed by the bolometer as indicated by the dc substitution bridge to the power absorbed as indicated by the difference between the forward power and the sum of the transmitted and reflected powers. Thus, if the apparent efficiency is -3 dB this means that the dc substitution bridge used with the test bolometer indicates that one-half the actual power is *apparently* absorbed by the bolometer. The actual power is measured (indirectly, of course) by other laboratory power meters and by reflection coefficient measurements.

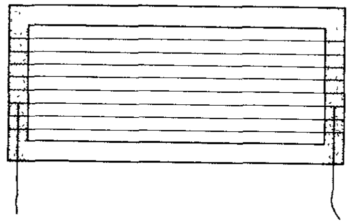


Fig. 2. A wire-grid bolometer similar to that of Fig. 1, but with wires oriented in the orthogonal direction.

Results of Tests on Experimental Metal-Coated Glass Fiber Wire-Grid Bolometers

Apparent efficiencies of $+0.04$ to -2.55 dB were measured for the first glass-fiber bolometer with power levels of 5 to 20 mW. This bolometer, of the type in Fig. 1, consisted of a lucite frame with 21 strands of glass fiber. Lucite used in the frame was found to be a poor frame material because of its thermal instability, and mycalex was used in later devices. A similar 21-strand bolometer of 500 ohms resistance and an 8-strand bolometer of 900 ohms resistance with strands horizontal (see Fig. 2) were then constructed and tested. These yielded apparent efficiencies between -1.2 dB and $+0.78$ dB in the 3.0- to 7.4-Gc frequency range. The TE_{10} mode was used to test the vertical-strand bolometer and the TE_{01} mode was used to test the horizontal-strand bolometer. Long, smooth input and output waveguide tapers were the mode transducers and waveguide-to-waveguide transformers.

A second set of the two types of bolometers was made with terminal resistances of 170 ohms and 700 ohms. Both bolometers were placed in the waveguide during testing but only one indicated that it absorbed power since only one mode at a time was present (either the TE_{10} or TE_{01} mode). The vertically polarized bolometer in this second set yielded apparent efficiencies of $+0.2$ to -0.8 dB for eleven measurements from S to X band, and the horizontally polarized bolometer yielded

+0.3 to −0.5 dB for three measurements at 6.4 Gc.

In addition to the above tests using the TE_{10} and the TE_{01} modes, these same metallized-glass-fiber bolometers were tested using the TM_{11} mode at 10.6 Gc/s. Here the frequency range was limited by the mode-generating equipment, since a relatively pure TM_{11} mode was desired. It was found that placing the two cross-polarized bolometers as close as possible yielded the most consistent results. Mode conversion after reflection and the inability to measure transmitted power by conventional means introduced inaccuracies in the measurements due to wave components that could not be accounted for. Still the results for the TM_{11} mode measurements were not greatly different from TE_{10}- and TE_{01}-mode measurements for the case of two closely spaced bolometers. Thus, in the TM_{11} mode, for the bolometers closely spaced and with the vertically polarized bolometer nearest the generator, an apparent efficiency of −0.8 dB was measured with 10-mW incident (the power in the two bolometers was summed), and with the horizontally polarized bolometer nearest the generator, apparent efficiencies of −1.2 and −0.9 dB were measured. Reflected power in the incident mode was used in the calculation but transmitted power was not known. For the bolometers separated from each other about four inches in the waveguide the apparent efficiencies were −1.7 and −1.5 dB for the vertically polarized bolometer nearest the generator, and −4.0 and −4.7 dB for the horizontally polarized bolometer nearest the generator. The above results are based on the total power in two bolometers. The bolometer with vertical elements was apparently more efficient than the one with horizontal strands for rectangular (*S*-band) waveguide propagating the TM_{11} mode at 10.6 Gc. This conclusion was based on the fact that the vertical-strand bolometer indicated about twice as much power as the horizontal-strand bolometer regardless of which was near the generator. Undoubtedly, the bolometer resistance match to the incident TM_{11} mode was significant here, and opposite results might be obtained with other values of resistance for the two cross-polarized rectangular bolometers. Measurements on the same bolometers in the TM_{11} mode at 8.2 Gc yielded apparent efficiencies of −1.6 dB for the case of vertical strands nearer the generator and −3.6 dB for the case of horizontal strands nearer the generator. The bolometers were spaced about four inches from each other in this case. Since better results were obtained with close spacing of the two cross-polarized rectangular bolometers it was felt that two closely spaced cross-polarized, but otherwise identical, square bolometers would be a still more useful configuration, and subsequent bolometers using Wollaston wires were made in square format for *S*-band and higher frequencies.

Experimental Wollaston-Wire-Grid Bolometers

The successful use of Wollaston wire in the bolometers depended on devising a method of supporting the fragile platinum strands of approximately 0.00005-in diameter. (This is less than two microns, or about three optical wavelengths.) A strand of such fine wire 2.7 in long (2.7 in is the clear opening in the square bolometer frame) has a slenderness ratio of about 50 000, which corresponds to a tightly stretched 16 AWG wire 200 ft long. The strands of pure platinum wires, unsupported except at the two ends, invariably broke after or during removal from the etching bath or wash water. Glass fibers similar to those used in the construction of the deposited gold-coated glass-fiber bolometers were used to support the platinum wire along its length. A few long spiral turns of the silver-sheathed wire were wrapped around a glass fiber which was affixed to the frame with wax preparatory to etching. Before etching, the ends of the wires were cemented to the conductive strips on the frames using conductive cement and the portions to be protected from the acid bath were covered with wax. It was found that too many spiral turns would cause the platinum wire to break. The etched platinum wire, upon examination under a microscope, was seen to cling to the glass fiber. Although tension released by the etching process could cause such clinging, there appeared to be a natural adhesive tendency between the glass fiber and platinum wire. In the above process Apiezon-H wax No. 353-76 was used as an acid-resistant coat. This wax is soluble in trichlorethylene. Etching was accomplished by immersion for 5 minutes in a 50 per cent solution of nitric acid. A microphotograph (×100) of a short section of glass fiber and Wollaston wire is shown in Fig. 3.

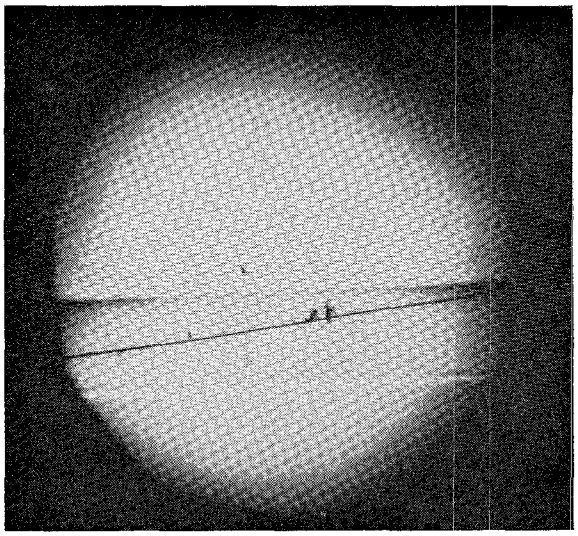


Fig. 3. Microphotograph (×100) of section of glass fiber and Wollaston wire.

Initially a four-strand Wollaston-wire-grid bolometer was made on a rectangular frame for *S*-band, and when the method of construction proved feasible, two square-frame bolometers 2.7 in ID were constructed with 20 strands each. The calculated bolometer resistance based on the manufacturer's data of 24 000 ohms/ft for the

Wollaston wire is 270 ohms and the resistance measured with an ohmeter was 265 ohms for each bolometer. Measurements on these bolometers from 2.8 to 8.4 Gc yielded apparent accuracies of $+1.25$ to -0.65 dB. The power indicated by the bolometer that was polarized perpendicular to the E-field of the incident TE_{10} wave (both bolometers were in the waveguide during measurement) was about 20 dB below that measured by the parallel-polarized bolometer.

Measurements on the square Wollaston-wire-grid bolometer in the TM_{11} mode did not, however, yield as good results as some of those obtained with the two closely spaced rectangular metallized glass fiber bolometers. The two essentially identical, square Wollaston-wire-grid bolometers were so close to each other in resistance that it was feasible to connect the two in parallel and make a single power measurement. Measurement efficiencies for the TM_{11} mode ranged between -2.0 and -4.1 dB at 10.6 Gc, the lowest figures again being obtained for vertical orientation of the grid wires nearest the generator. A photograph of the two square Wollaston-wire-grid bolometers, mounted for insertion between two S-band waveguide to square waveguide tapers, is shown in Fig. 4.

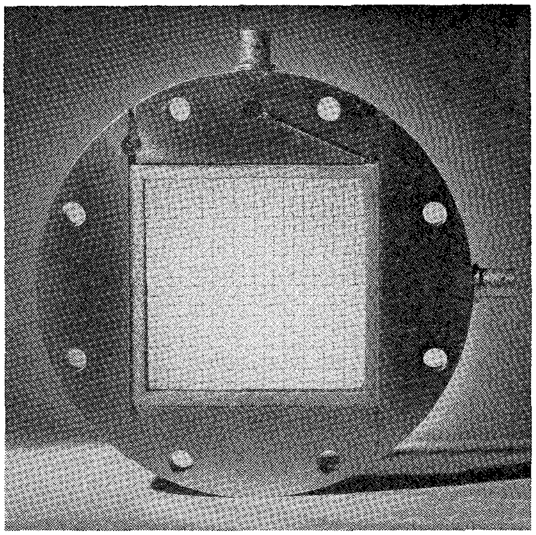


Fig. 4. Two cross-polarized Wollaston-wire-grid bolometers mounted for insertion in square S-band waveguide.

A rough estimate of the power handling capability of the Wollaston-wire-grid bolometer can be obtained by extrapolating the capacity of a single-wire bolometer. If a 50-ohm single wire bolometer can handle 10 mW, then a wire-grid bolometer of 20 strands, each 3 in long, can handle 24 watts. No tests of the power handling capability of the wire-grid bolometer were made.

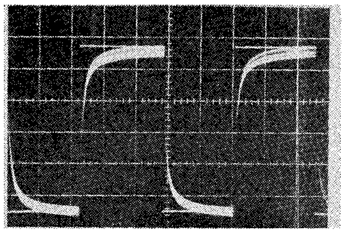
The Wire-Grid Bolometer as a Detecting Element

Although the wire-grid bolometer and its predecessor the thin-film bolometer were originally proposed as multimode power-measuring devices they are also useful as detecting elements in an overmoded waveguide system in which a broad spectrum of harmonic (and anharmonic) frequencies has but one modulation envelope.

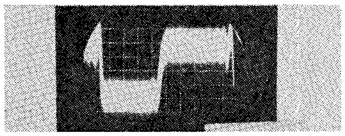
Various experimental multimode bolometers were tested as detecting elements in a laboratory recording system using 1000-c/s modulation. The system was originally designed for commercially available 100- and 200-ohm bolometers. The speed of response of the experimental bolometers appeared to be adequate for the 1000-c/s modulation in all cases, but there was, in some cases, a mismatch of the bolometer resistance and the amplifier input resistance, which reduced the measuring sensitivity a moderate amount. Large differences were observed in sensitivity between the various bolometers tested, and these could only be due to differences in the microwave power-to-incremental resistance conversion efficiency of the various bolometers.

A thin-film bolometer has a higher surface-to-volume ratio than the same weight of metal in the form of wires. Its temperature change and therefore its resistivity change should be less than that of the wire for the same power input. Hence, in the sense implied here a thin-film bolometer should have lower sensitivity as a detector than a Wollaston-wire bolometer, whether of the commercial variety or of the new multimode type described herein. Comparative tests using a PRD Model 627 bolometer in a coaxial mount as a sensitivity reference showed that a 4-strand Wollaston-wire-grid bolometer (the four evenly spaced wires were mounted near the center of the frame) in S-band waveguide was 29 dB less sensitive than the standard. An impedance mismatch could account for no more than 2 dB of that figure, bringing it to 27 dB. A metal-deposited-glass-fiber bolometer was found to have -61 dB relative sensitivity and a thin-film bolometer -67 dB relative sensitivity. Despite the apparent low relative sensitivity of these experimental bolometers they are still capable of measuring power to the reported accuracy.

In general, a direct relationship exists between sensitivity and time constant in an efficient system. This was demonstrated by comparing the responses of bolometers to square-wave modulated RF. Figure 5 shows the oscilloscope pattern of two dc-biased experimental bolometers to square-wave modulated RF power. Both patterns show approximately the same envelope deterioration, each caused by the time constant of its bolometer; however, the 4-strand rectangular Wollaston-wire-grid bolometer of Fig. 5(a) was modulated with 500-c/s square wave while the thin-film bolometer [see Fig. 5(b)] was modulated with 100-kc square wave. The thin-film bolometer in fact showed passably good response at 1 Mc, whereas the Wollaston-wire-grid bolometer response became a sawtooth pattern whose amplitude was only a small fraction of its full height at 100 kc/s. A second oscilloscope pattern of a Wollaston-wire-grid bolometer (20-strand, square-shaped) is shown in Fig. 6. Here the shape of the re-



(a)



(b)

Fig. 5. Response of multimode bolometers to square-wave-modulated RF. a) Four-strand Wollaston-wire-grid bolometer, 1000 c/s. b) Thin-film bolometer, 100 kc.

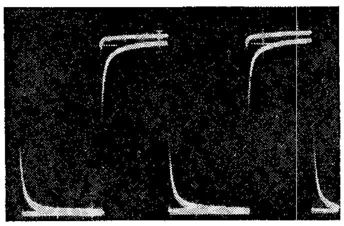


Fig. 6. Response of 20-strand, square-grid, Wollaston-wire bolometer to square-wave modulated RF, 500 c/s.

sponse is similar to that of the other two but the modulation frequency was 500 c/s. A PRD Model 627 coaxial bolometer showed a similar response pattern at 500 c/s. Measurements on response patterns at higher modulation frequencies indicated that the time constant of Wollaston-wire-grid bolometers was about 10 μs. The time constant of thin-film bolometers was not measured, but from the comparative tests it is believed to be about 100 ns.

Conclusions

The Wollaston-wire-grid bolometer, which evolved from the experimental thin-film multimode waveguide bolometers, is more stable and reproducible than the thin-film bolometers. However, two orthogonal wire-grid bolometers must be used to intercept all possible modes. All three types of multimode bolometers, the thin-film bolometer, and the two types of wire-grid bolometers (one using Wollaston wire and the other metallized glass fibers) have been shown to be useful in measuring the total power in several modes.

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