A Universal Wall-Current Detector*

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Summary—A universal X-band waveguide detector has been developed which offers the possibilities of a broad-band untuned detector with a stable frequency characteristic.

The wall-current detector is a reflectionless two-port with an insertion loss, less than 0.05 db, no extra phase-shift, a sensitivity of about 10 mv/mw and a frequency characteristic which repeats within ±0.1 db over the 8.2–12.4 Gc band for any 1N26.

This performance made it possible to flatten the output of a Hewlett-Packard sweep oscillator (as seen by another wall-current detector) within ±0.15 db over the whole X band. As a result many frequency-dependent measurements can now be done automatically with reasonable precision.

Plotters and reflectometers will be simplified, resulting in a higher precision.

Circular and ridge waveguide types have also been made. The latter seems very promising for an ultra broad-band detector.

A sum detector and a difference detector have been made. They can be used for phase-sensitive detection, zero measurements, etc.

The wall-current detector can easily be scaled down to mm waves.

I. Introduction

Most MICROWAVE detectors are based on measuring the *electric* field. A probe or the semiconductor diode itself is placed in a position where the electric field is different from zero. If the conduction current excited in the probe or diode is equal to the displacement current before the probe or diode was inserted, no perturbation occurs and the detector can be said to be ideal.

Currently used X-band broad-band detectors, *e.g.*, Philips PP 4225 X, are based on electric coupling and have a (voltage) reflection coefficient $R \leq 0.2$ and a frequency characteristic (sensitivity as a function of frequency) identity of a few db. For many applications this is not good enough.

A much smaller reflection can be obtained with a broad-band untuned probe on a waveguide terminated by a matched load. Although the variation of the sensitivity as a function of frequency can be much smaller, the sensitivity is very poor. This is caused by the fact that the usually applied diodes are coaxial types, provided with a ceramic bead between inner and outer conductor of the coaxial system. In this way a condenser with a rather low impedance shunts the high impedance diode. This situation can be beneficial if detectors with identical frequency characteristics are wanted, as the diode itself hardly influences the behavior of the detector. In order to get a good sensitivity, the detectors must be used at a low impedance base. This can be achieved by making a detector based on measuring the *magnetic* field which can be done with a loop or a coupling hole.

Although it is impossible to make an ideal detector, whether electric or magnetic, the approach to the magnetic type is far more promising. Tischer[1] has succeeded in making an almost perfect magnetic probe by adding a compensating wire to the normal loop. However, owing to the more delicate construction, it is very difficult to get detectors with identical frequency characteristics. Moreover a coupling loop is hard to make for mm waves.

If the coaxial diode in the untuned probe is put at a place where the electric field is zero in such a way that part of the wall current is forced to pass the diode, a wall-current detector is obtained. Owing to the simple construction, reflectionless broad-band detectors with frequency characteristics identical within a few tenths of a db over the whole X band can be made. Its construction is so simple that the wall-current detector can easily be scaled down to mm waves.

As the untuned probe may be regarded as a voltmeter, the wall-current detector can be seen as an ammeter. If used as a broad-band detector the wall-current detector has several advantages over the untuned probe, *viz.:*

1) the sensitivity is at least 10 db higher,
2) a better identical frequency characteristic can be obtained,
3) it is easier to make without reflection ($|R| \leq 0.005$).

Compared to the usual broad-band detectors its sensitivity is 7–10 db smaller.

II. Principle of Operation

In the sidewall of a rectangular waveguide an axial slit p and the coaxial line of length q are shunted by the condenser C of a modified coaxial diode 1N26(R) or IN31. Fig. 1 shows a typical configuration of a wall-current detector. A part of the wall current passes the detector. To avoid short-circuiting of the rectified current, a quarter-wavelength choke has been built along the outer conductor of the diode D. The RF voltage v across the condenser C causes a dc voltage V across the detector load. Modified coaxial diodes are chosen for the reason already mentioned in Section I and expressed by the inequality

$$\frac{1}{\omega C} \ll Z_D, \tag{1}$$

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[1] F. J. Tischer, "Rotatable inductive probe in waveguides," Proc. IRE, vol. 43, pp. 974–981; August, 1955.

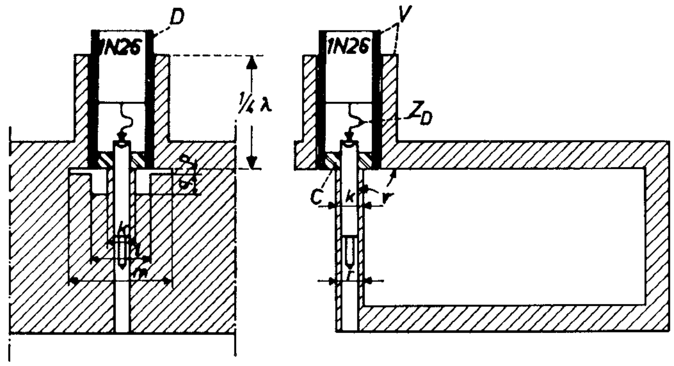


Fig. 1—(a) Longitudinal section of a wall-current detector. (b) Cross section of a wall-current detector.

Z_D being the RF impedance of the diode. The value of C is about 0.7 pf for the types IN26(R) and IN31. The diode itself is connected to this condenser with very short leads, so that, if diodes of the same type are used, the frequency characteristic of the individual detectors is hardly influenced by the diode itself.

The most important feature of wall-current detectors is that their frequency characteristics are almost identical. No complicated construction or absorbing material spoils the identity. The detectors differ only in sensitivity, which however is reduced due to inequality (1).

Terminated by a perfectly matched load it behaves as a broad-band reflectionless detector. The phase shift is too small to be measured. The insertion loss is less than 0.05 db. Consequently another feature of the wall-current detector is that it can be used as a four pole with hardly any reflection, additional phase shift or losses.

III. Qualitative Explanation of the Broad-band Characteristic

The frequency dependence of the time-average power flow in a propagating H mode is given by[2]

$$P \propto \frac{1}{\lambda\lambda_g} H_z^2. \tag{2}$$

For the H mode the (transverse) surface current on the side wall is proportional to H_z, so the frequency-dependent relation between the power flow and the wall current i per unit length becomes

$$P \propto \frac{1}{\lambda\lambda_g} i^2. \tag{3}$$

For constant power flow the frequency characteristic of the wall-current detector would not be flat if i were to be detected directly.

In order to get a detector with optimum sensitivity a circuit given in Fig. 3 is applied. The dimensions are so chosen that hardly any reflection occurs in the waveguide. Part of the wall current, denoted by i_c, is forced pass the detector

$$i_c^2 \propto \left(\frac{i_c}{i}\right)^2 P\lambda\lambda_g. \tag{4}$$

The relation between the RF voltage v or v^2 (for square-law detection) as measured by the diode and the power flow P becomes

$$v^2 \propto \left(\frac{i_c}{i}\right)^2 P\lambda^3\lambda_g. \tag{5}$$

In order to obtain a fairly flat frequency characteristic for constant power flow, the following condition must be fulfilled

$$\frac{i_c}{i} \propto \frac{\omega}{\sqrt{\lambda\lambda_g}}\cdot \tag{6}$$

Experiments have proved that this could be achieved rather well with a construction of the detector mount as given in Fig. 2(a) and in the detailed drawing of the compensation circuit shown in Fig. 3. The presence of the condenser C makes i_c/i already more or less proportional to ω. It is reasonable that condition (6) holds for a construction as given in Fig. 3, for the smaller the wavelength, the bigger the hole expressed in wavelengths and the greater i_c with respect to i.

Fig. 4 (p. 115) shows the frequency characteristics of several types of coaxial diodes. Due to minor differences in the construction of the types IN26, IN26R and IN31, probably due to different capacity of the condenser C, the slopes of the characteristics are different. These can be made equal by changing the diameter k of the inner conductor of the coaxial part of the circuit. If this coaxial part is omitted ($q=0$) the frequency characteristic tends to become hollow. As it is rather difficult to change k continuously, it is also possible to change the slope of the frequency characteristic by using the rotary part in the construction of Fig. 2(a). From Fig. 3 it can

[2] R. E. Collin, "Field Theory of Guided Waves," McGraw-Hill Book Co., Inc., New York, N. Y., p. 179; 1960.

(a)
(b)
(c)

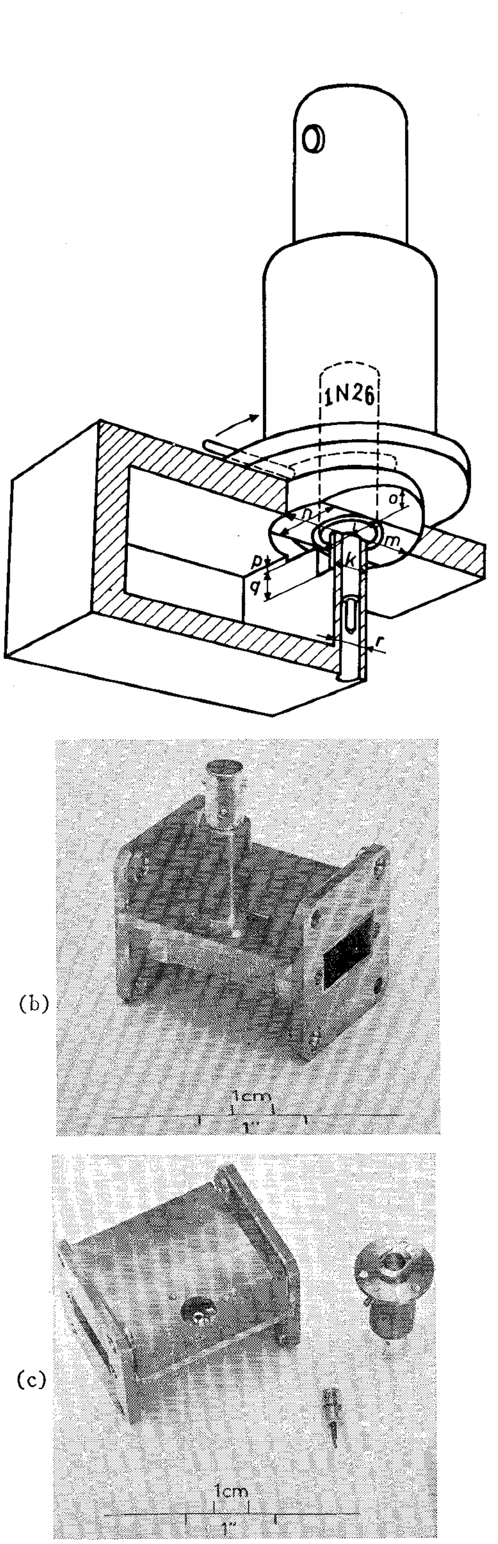


Fig. 2—(a) Internal construction of the wall-current detector

$k=2.5-3.5\phi$ $\quad o=2$
$l=6\phi$ $\quad p=0.1$
$m=10\phi$ $\quad q=4$
$n=6$ $\quad r=2.6$ (all dimensions in mm).

(b) Photograph of the wall-current detector. (c) Photograph of the disassembled wall-current detector.

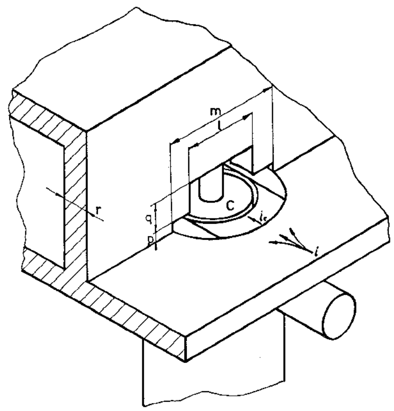


Fig. 3—Internal construction of the compensation circuit.

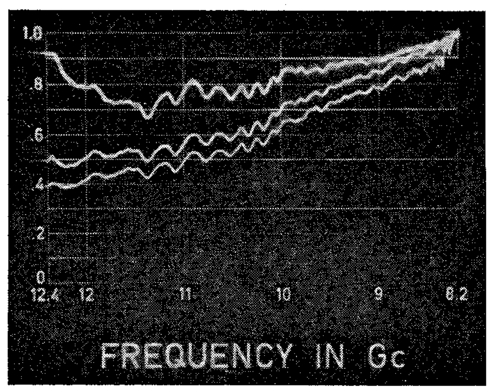


Fig. 4—Frequency characteristics of several diodes. Upper curve 1N26R. Middle curve 1N26. Lower curve 1N31. 1.0 corresponds to 10 mv dc. $k=\phi$ 3 mm.

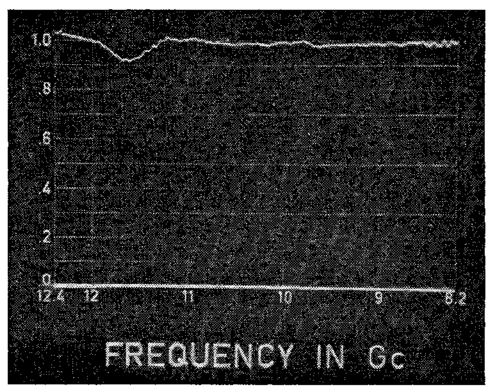


Fig. 5—Leveled output of a H/P 686 C sweep oscillator (1N26 diodes have been used, $k=\phi$ 3.5 mm).

be seen that this rotation also results in shunting the condenser C by an external reactance in such a way that compensation for different values of C can be obtained.

Also, in order to obtain a frequency-independent output from the detector, the generator power has to be constant. This is not the case, however, in practice. As it is not difficult to get identical frequency characteristics for wall-current detectors, the simplest solution is to accept a fairly flat frequency characteristic (maximum variation less than 3 db). By using one detector as a leveler the output of the others could be made flat within ≥ 0.13 db (see Fig. 5).

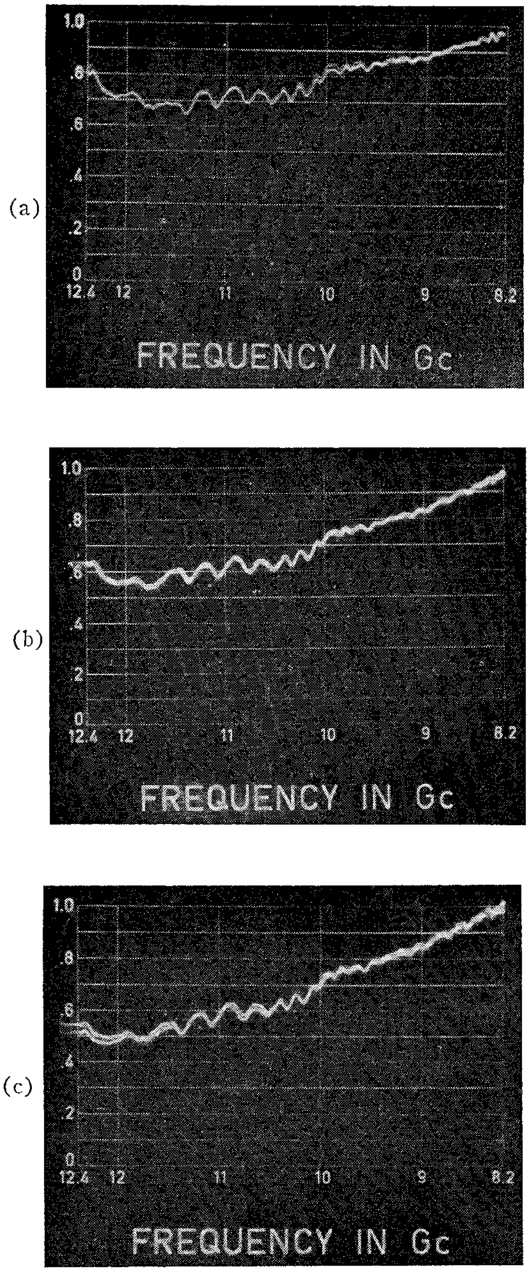


Fig. 6—(a) Frequency characteristics of two 1N26R diodes, $k=\phi$ 2.5 mm. (b) Frequency characteristics of two 1N26 diodes, $k=\phi$ 3.5 mm. (c) Frequency characteristics of two 1N31 diodes, $k=\phi$ 3.5 mm. All after slope and sensitivity compensation. 1.0 corresponds to 10 mv dc.

IV. Performance

As the wall-current detectors are reflectionless four poles ($|R| \leq 0.005$), the simplest way to compare their performance is to put them one behind the other and have the last one terminated by a matched load. In order to ensure square-law detection over a wide range, the microwave power level has been kept below 1 mw. As the sensitivity is at least 10 mv/mw, the dc voltage across the 1 MΩ input impedance of the oscilloscope is about 10 mv. Typical broad-band characteristics can be seen in Fig. 4.

It is reasonable that the most identical frequency characteristics can be obtained when minimum compensation is required. This means that diodes of the same type and preferably of the same manufacturer must be used. Fig. 6 demonstrates the identity of several types of diodes (1N26, 1N26R and 1N31) after slope and sensivitity compensation. The detectors are identical over the whole X band within ≥ 0.2 db. If the choke does not work very well, it spoils the identity of the detectors. In order to prevent this, a three-quarter wavelength choke was necessary. The capacity of the BNC-290 U connector together with the choke became about 13 pf, so its reactance is 50 Ω at 250 Mc. This is the only limitation to the maximum modulation frequency as far as the detector mount is concerned.

The sensitivity of the wall-current detector seems rather low, but for most uses it is quite sufficient. The sensitivity can be increased by reducing the height of the waveguide at the position of the detector. The sensitivity could easily be increased by a factor of four. If the coaxial diode with its shunt capacity C is replaced by a small low impedance diode, probably a much more sensitive broad-band detector could be obtained, but at the expense of the identity of their frequency characteristics.

If linear detection occurs, the slope of the frequency characteristic may change somewhat, but this can be compensated in the same way as has been done for difference in the capacity C.

V. Applications of the Wall-Current Detector

By applying wall-current detectors many microwave circuits can be simplified, resulting in a higher precision and a better broad-band performance.

One of the most important applications, where use is made of the identical frequency characteristics, is the *leveler*.

If the output of one wall-current detector, usually called the leveler, is amplified by a dc or AF amplifier with an amplification factor of a few thousand and fed in the right phase to the external modulation input of a Hewlett-Packard 686 C sweep oscillator, the output of this oscillator as seen by another wall-current detector placed behind the leveler, can be made flat within ± 0.15 db (see Fig. 6). The leveled output is about the average of the unleveled one. In this way it is possible to measure the transmission of two-ports as a function of frequency directly. Care must be taken that no standing waves occur at the position of the leveler. This will require that a frequency independent pad or isolator has to be placed behind the leveler.

Reflectometers, usually provided with two high-directivity directional couplers, can now be made with one directional coupler (see Fig. 7). Wall-current detectors are placed in front of the matched loads in the side line. Besides a simpler construction a much higher precision has been obtained because variation in the coupling, due to frequency dependence, is no longer important. However, the influence of standing waves on the coupling

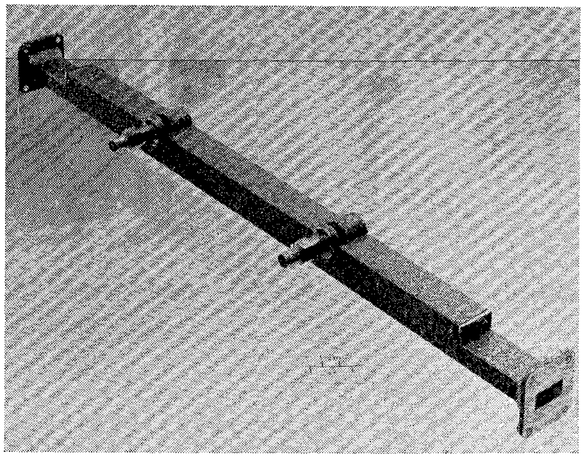
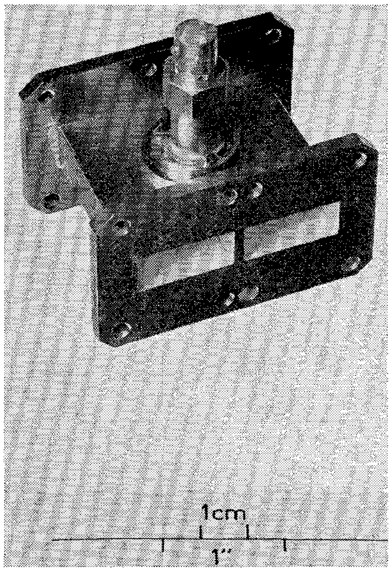
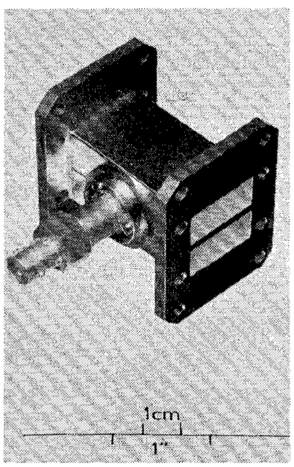


Fig. 7—Reflectometer directional coupler (10 db) with built-in detectors.



(a)



(b)

Fig. 8—(a) Sum detector. (b) Difference detector.

still remains. A 10-db coupler proves to be suitable if a Hewlett-Packard Ratiometer type 416A is used.

If the argument of the complex reflection coefficient is also wanted, a *plotter*[3] can be made, using wall-current detectors.

As the coupling between the waveguide and the detector is rather weak, being 20–30 db down, two waves can be coupled to the same detector with hardly any interference. Based on this principle a *sum detector* and a *difference detector* have been made (see Fig. 8). For this purpose a detector is placed in the common wall of two waveguides with either the narrow or the broad faces against each other. The coupling between both waveguides is about 40–60 db. Detectors of this type can be used for mixers without the need of a directional coupler. The sum detector and the difference detector are, in fact, phase-sensitive detectors for microwaves and are able to simplify well-known measuring methods,[4] although a fast plotter[3] is preferable in most cases.

VI. Other Possibilities

Although the wall-current detector has first been realized for rectangular waveguides, there is no restriction whatsoever as to cross section or type of transmission line. A single ridge-waveguide type was made with the inner conductor of the coaxial diode in the ridge and the detector mount in the middle of the broad face of the rectangular ridge waveguide. The maximum height of the tapered ridge was equal to half the height of the waveguide and the width was equal to twice the wall thickness of a normal drawn X-band waveguide, *i.e.*, 2.6 mm. The same detector mount as used for the normal rectangular waveguide type has been used. Excellent performance has been achieved and this component seems very promising for an ultra-wide-band wall-current detector.

A circular waveguide type detector has been made, which is at least 40 db more sensitive for one plane of polarization than for another perpendicular to it.

Instead of a diode, a thermistor or barretter of the same construction can be used, allowing broad-band power measurements to be made.

As already mentioned in Section IV a reflectionless fairly sensitive broad-band detector probably can be made, when a special low impedance diode is available.

VII. Future Developments

By measuring the current in the way described above a number of useful extensions can be made of this type of detector. For instance, interaction of currents of different modes can be measured. A simple frequency dis-

[3] F. C. de Ronde, "An Automatic Swept-Frequency Smith-Chart Plotter," presented the Millimeter and Submillimeter Conference, Orlando, Fla.; January 7–10, 1963.

[4] J. E. Drummond, "Plasma Physics," McGraw-Hill Book Co., New York, N. Y., p. 107; 1961.

criminator can be made with a circular waveguide detector, where TE_{01} and TE_{11} modes interfere. The detectors must be situated in the same transverse plane but at opposite walls in such a way that the coupling with the TE_{11} mode is maximum. A small asymmetry is already sufficient to excite the TE_{01} mode. Usually the guide is below cutoff for this mode, which means that it forms a resonator for the TE_{01} mode. As the detector currents due to this mode are antiphase and those caused by the TE_{11} mode are in phase, the differential voltage of the two detectors as a function of frequency gives a discriminator curve.

If condition (1) is fulfilled, wall-current detectors with identical frequency characteristics can be constructed for frequencies lower and higher than X-band frequencies and for other types of transmission lines.

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First-Order Theory for Oblate and Prolate Anisotropic Artificial Dielectrics*

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Summary—**Equivalent expressions for the electric permittivity and magnetic permeability tensors of artificial dielectrics are derived. These are expressed as functions of particle dimension, shape and density and also as a function of the incident electromagnetic beam direction with respect to the orientation of the particle. Only the case of a uniform density of equally oriented particles is considered. The results are valid in first order for prolate and oblate spheroids. Spheres and disks are obtained as limiting cases.**

INTRODUCTION

THE DEVELOPMENT of microwave applications in the two last decades caused an extension of optical techniques to this region of the electromagnetic spectrum. In 1948, Kock[1] proposed that a three dimensional lattice of identical metallic particles, disposed as atoms in a crystal, would act as an "artificial" dielectric. Equivalent arrangements may be obtained in different ways,[2] but this paper will be restricted to the important case of lattices of oriented particles.

Some of the more important applications of artificial dielectrics are: phase delay lenses, filters and polarization transformers. The physical mechanism is very simple: as a convenient wavelength electromagnetic wave is incident on a metallic particle, electric dipole moments and currents are induced in the particle. This will produce a phase delay in the electric and magnetic vector fields, in the same way in which it occurs in natural dielectrics. These delays depend upon the magnitude of the induced moments and currents, which in turn depend on the shape and the orientation of particles. These induced moments and currents can be accounted for by the proper permittivity and permeability tensors.

THE DEBYE AND MOSSOTI APPROXIMATIONS

If $\boldsymbol{E}^1$ is the local field, $\boldsymbol{p}$ the mean dipole moment per particle, then, under a quasi-static field approximation, $\boldsymbol{p}=\alpha\boldsymbol{E}^1$, where α is the polarizability. The polarization vector $\boldsymbol{P}$ becomes $\boldsymbol{P}=N\boldsymbol{p}=N\alpha\boldsymbol{E}^1$, where N is the number of dipoles per unit volume. As $\boldsymbol{P}=\boldsymbol{D}-\epsilon_0\boldsymbol{E}=(\epsilon-\epsilon_0)\boldsymbol{E}$, where $\boldsymbol{E}$ is the applied field, there is

$$N\alpha\boldsymbol{E}^1 = (\epsilon - \epsilon_o)\boldsymbol{E}.$$

Debye's approximation consists of neglecting the contribution of other particles to $\boldsymbol{E}^1$ and in the consequent identification of $\boldsymbol{E}$ with $\boldsymbol{E}^1$. This leads to

$$\epsilon_r = \frac{N\alpha}{\epsilon_o} + 1,$$

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[1] W. E. Kock, "Metal-lens antennas," PROC. IRE, vol. 34, pp. 828–836; November, 1946.

[2] John Brown, "Artifical dielectrics" in "Progress in Dielectrics," J. B. Birks and J. H. Schulman, Ed., John Wiley and Sons, Inc., New York, N. Y., vol. 2, pp. 193–225; 1960.