A Simple and Rugged Wide-Band Gas Discharge Detector for Millimeter Waves

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Abstract—Detection of 4 and 2 millimeter waves by a small, low-pressure, anomalous burning glow discharge in He or Ne is described. The responsivity and the noise equivalent power are discussed. Typical values are presented in a table: the former is found to be about 50 V/W, the latter about 5 μW. The device is linear over about 30 dB, it has a LF bandwidth of about 50 kc/s and the same tube can be used both for detection of 4 and 2 mm waves by simply raising the applied dc potential a few volts. Since the device is very rugged it can withstand a high local oscillator power, so that in a synchroneous detection circuit the noise equivalent power can be about 10^{-11} W at 1 c/s bandwidth.

I. Introduction

IT IS WELL KNOWN that the development of suitable detectors of millimeter and submillimeter waves, with reasonable sensitivity and response time, presents a serious problem to those engaged in the extension of the frequency range of high-frequency generators and components.

Various principles [1], [2] can be used for detection, the most important among them being thermal or photoconductive effects or point-contact rectification. Thermal effects generally imply long response time, whereas devices based on photoconductive effects require high magnetic fields and operate efficiently only at liquid He temperatures.

Millimeter waves are very often detected with a semiconductor point-contact diode [1], [3]. Though this device gives satisfactory performance at the longer wavelengths, an important drawback is that the RC time due to the high point-contact capacity and the silicon bulk resistance is relatively long. To overcome this disadvantage of the mm wave version a tiny, delicate structure has been used. This implies that the detector has a low burn-out energy and is hence very limited in its power-handling capacities.

As most detectors are not used at minimum detectable signal level many people are interested in a rugged detector as easy in operation as an X-band crystal diode.

This paper deals with a mm wave detector based upon the rectifying properties of a gas discharge, which satisfies the above requirements.

Practical arrangements for microwave detection by a gas discharge plasma have been mentioned in the general [4]–[11] and in the patent [12]–[16] literature, of which none operates in the mm wave region. We have already studied the detection of 3 cm waves by a low-pressure glow discharge [17]. In order to explain the effects measured, a detailed study of the electronic and ionic processes occurring in the cathode fall was made and it was found that this small region is particularly sensitive to disturbances of a frequency near the so-called pseudo plasma frequency ω_p for plane electrode configuration given by

$$\omega_p^2 = \frac{ne^2}{m\epsilon_0} = 2\frac{e}{m}\frac{V_0}{d^2}. \tag{1}$$

Here V_0 is the potential difference over the cathode fall, being very close to the anode-cathode potential difference in the absence of positive column or anode fall, d is the thickness of the cathode fall region, n the uniform ion density in this region, and $-e$ and m the charge and mass of the electron. It was shown that microwave power increases the number of ionizations per unit time and volume, which generates an extra current Δi through the resistance R_v, hence an extra potential difference $R_v\Delta i$ occurs, which is a measure of the incident microwave power. This causes an equal potential drop over the discharge, whence the differential resistance $R_i = dV/di$ starts to play the role of the internal impedance of the extra current generator. The actual circuit and the equivalent circuit from the LF point of view are given in Figs. 1 and 2. As can be seen from Fig. 1 the detector had a coaxial electrode configuration and the same dimensions as a 3 cm semiconductor detection crystal.

Section II will show how the tube should be modified to form a good detector in the 4 and 2 mm wavelength regions. In Section III typical values of all parameters concerned and typical results for the responsivity, noise equivalent power and response time will be given. In Section IV the gas discharge will be discussed in a synchronous detection circuit. It will be shown that, as a high local oscillator power may be applied due to the high burn-out power, this mode of operation disposes of much of the main drawback, the high noise voltage. It will be shown that the minimum detectable signal level is reduced to about 10^{-11} W, which is slightly less than the level reported by Meredith and Warner [1] using a Ge rectifier in a 2 mm video receiver.

The most salient features are summarized in Section V.

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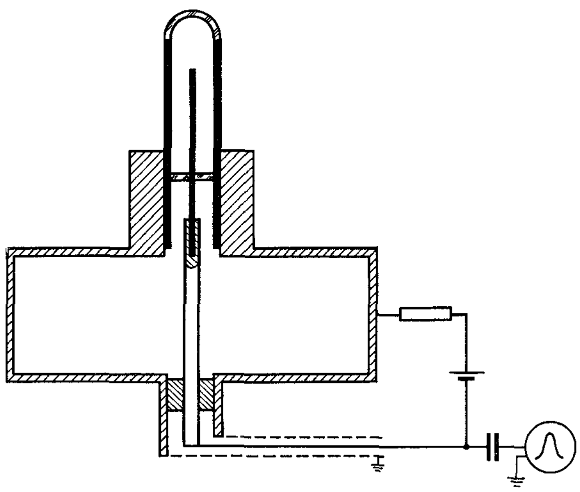

Fig. 1. The coaxial discharge tube mounted in a waveguide crystal holder for 3 cm microwave detection showing a cross-section through the waveguide and the detector.

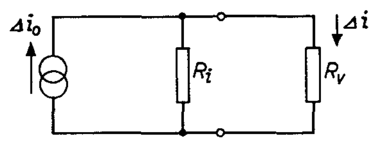

Fig. 2. The equivalent circuit from the LF point of view with the LF current generator. When instead of the current source representation, the voltage source representation is used, we only need $\Delta V_0 = R_i \Delta i_0$.

II. Experiments at 4 and 2 mm Wavelength

In an earlier paper on 3 cm wave detection [17] we mentioned the possibility of extending the detectable frequency range into the millimeter wave region. A tube with applied potential $V_0 \approx 650$ V and dc $i_0 \approx 15$ mA presented a rectified potential of about 50 mV at an incident microwave power of about 10 mW; this tube was of no practical use because of the high dc dissipation, 10 W, and low responsivity. No better results could be obtained in this way.

Some years ago the ZA tube was introduced [18] and used, with a relevant gas filling for different purposes. The schematic cross-section of a ZA tube is shown in Fig. 3. We have used this type of tube as a microwave detector in a component shown in Fig. 4 and to our surprise its performance was very good. In contrast with the arrangement for 3 cm wave detection, where the coaxial mode should be excited perpendicular to the waveguide axis, in the mm wave detection arrangement the waveguide axis and the coaxial conductor—the cathode—are in a straight line. The deformation of the field, occurring at the point where the microwaves enter the device through the more or less sharp point of the glass envelope, takes place gradually.

In this way, a considerable part of the microwave power enters the glass envelope and is lost for detection purposes. The performance can be raised by closing the waveguide with mica windows, thus making an integrated component. The cylindrical microwave component shown in Fig. 4 is connected with the rectangular 2 or 4 mm waveguides.

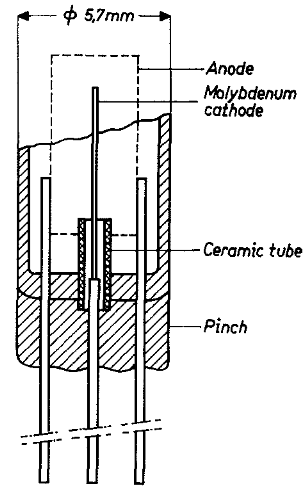

Fig. 3. Schematic cross-section of the gas-filled diode, showing the electrode configuration.

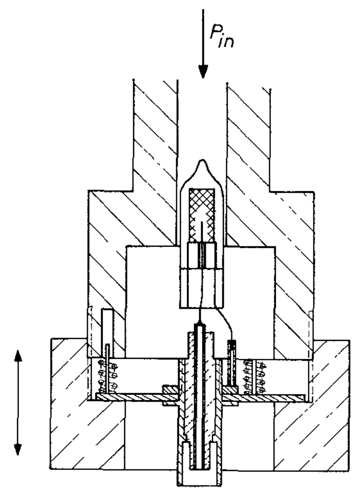

Fig. 4. The cylindrical waveguide component in use for efficient operation of the gas discharge detector. It fits closely in the component to give good thermal contact.

III. Typical Results of the Measurements

Millimeter wave detection with ZA tubes filled with He and Ne has been investigated at a pressure p in a range from 20 Torr increasing by 10 Torr steps up to 150 Torr. Below this range the performance of the detector decreases greatly and above the highest pressure the current $i \sim p^2$ becomes so great that the electrodes may be damaged. Also a large number of tubes having different cathode lengths have been tested.

All these tubes were exposed to microwave radiation of 2 and 4 mm wavelength, with 30 and 100 mW available power, respectively. The results of the measurements have been expressed in the responsivity γ, indicating the open circuit voltage per unit of incident power. The extra potential drop ΔV over the resistor $R_v \approx 5$ kΩ has been measured and in order to compare the results they are reduced to the open-circuit voltage ΔV_0 by multiplying ΔV by $(R_v + R_i)/R_v$ where R_i is the internal impedance. It will be shown later that γ does not depend on the incident power P over a wide range.

The parameters and their typical values are given in Table I.

TABLE I

			p (Torr)	V_0 Volt)	i_0 (mA)	W_0 (Watt)	R_i (kΩ)	ΔV_0 (mV)	γ (V/W)	NEP (dBm)
I	Ne	$l=6$ mm	100	122	12.6	1.5	1.4	2500	20	19
	$\lambda=4$ mm	$l=4$ mm	110	180	17	3.1	5	6000	50	20
		$l=2$ mm	90	180	8	1.5	5	6000	50	20
II	Ne	$l=6$ mm	100	150	20	3	1.8	550	20	16
	$\lambda=2$ mm	$l=4$ mm	70	180	13	2.3	5	2400	90	21
		$l=2$ mm	90	220	12	2.6	12.5	2800	110	19
III	He	$l=6$ mm	110	160	7.5	1.2	7.2	3500	35	15
	$\lambda=4$ mm									
IV	He	$l=6$ mm	80	180	20	3.6	5.5	80	8	10
	$\lambda=2$ mm									

The parameters of the tubes and the typical results of the measurements. Rows I and II refer to detection with Ne-filled tubes. They are subdivided according to the length of the cathode. Rows III and IV refer to detection with He-filled tubes.

It turns out that the Ne-filled tubes yield about the same results at 4 mm as at 2 mm wavelength, whereas the He-filled tubes yield somewhat better results at 4 mm, but much worse results at 2 mm. With Ne the best results were obtained at the active cathode length $l=2$ mm; with He no influence of active cathode length was found. We do not know how to explain this. It is the opinion of the authors that the very slow decrease in performance from 4 to 2 mm wave detection is a surprising result.

It should be emphasized that typical values are presented here which are representative of the major part of the pressure range investigated. Differences in performance among tubes of the same or slightly different parameters should be ascribed to slight differences and asymmetries in the form of the pointed glass envelope. This can be concluded from the fact that turning the tube about its own axis may change the output substantially. In order to appreciate the responsivity of our detector it is interesting to note that the guaranteed [19] responsivity of a semiconductor crystal detector is generally about 150 V/W between 26 and 170 kMc/s.

Apart from the responsivity γ, the noise equivalent power (NEP) is an important parameter for detection. Of course utility is great when γ is large and the NEP is low. However, gas discharges are notorious for high noise voltage. Detailed measurements on the noise output of a normal burning glow discharge have been made by van der Ziel and Chenette [20]. They found that over a wide frequency range, from about 100 c/s to 500 kc/s, the glow discharge could be represented by a high equivalent noise resistance R at room temperature T, according to

$$V_n^2 = 4kTR\Delta f. \tag{2}$$

Below the lower limit of this frequency range the noise output was much greater still and above the upper limit that LF impedance [21] began to be significant. This high equivalent noise resistance R at room temperature could be explained by introducing the dc resistance R_0 at the electron temperature as the real source of noise. From our investigations it followed that the electrons in the cathode fall are very hot, their temperature corresponding to about the ionization energy eV_i. However, this model as such does not apply in the range of anomalous burning used for detection. Generally, the noise increases when the discharge starts burning in this range. In the last column of Table I the noise equivalent power (NEP), in dB below 1 mW, has been given, to which level the microwave power should be reduced to yield roughly twice the peak-to-peak value of the noise voltage V_p. This value has been measured with a Tektronix oscilloscope, type 502 A, and is found to be of the order of 5.10^{-4}V over an open LF circuit. The voltage V_p is introduced here to represent the oscilloscope noise pattern width; neglecting 10 percent of the peaks we find $V_p \approx 5V_n$ [22]. The LF bandwidth, limited by the gas discharge, turns out to be 50 kc/s.

From the expression for thermal noise as used for a normal burning glow discharge the rms value of the noise voltage V_n using the relations discussed above, is given by

$$V_n \approx \tfrac{1}{5}V_p \approx (4kTR\Delta f)^{1/2} \approx (4eV_iR_0\Delta f)^{1/2}. \tag{3}$$

Assuming that this expression can be applied here we find with $V_i \approx 20$ V, $R_0 \approx 20$ kΩ and $\Delta f \approx 50$ kc/s that $V_n \approx 10^{-4}$ V, in accordance with the measured value. From the last column of Table I it can be seen that in our measurements the noise equivalent microwave power is about 10 μW, which corresponds, as has been said, to 0.5 mV and hence to a responsivity $\gamma \approx 50$ V/W, as actually measured.

A third interesting point is the linearity of the detector, that is to say, how well the relation $\Delta V = \gamma P$ is maintained over a large range. In Fig. 5 this relation is plotted on a double logarithmic scale as measured in Ne with a tube of cathode length $l=4$ mm, $V_0=150$ V, $i_0=17$ mA. It follows from this curve that the relation is well satisfied over three decades between the low and high voltage regions. In the first region the noise is dominant and in the second region higher-order terms limit performance because it gradually becomes more like a microwave discharge. In the experiment where about 1 W dc power is dissipated in the detector this effect starts to deteriorate the performance at about 100 mW microwave power level.

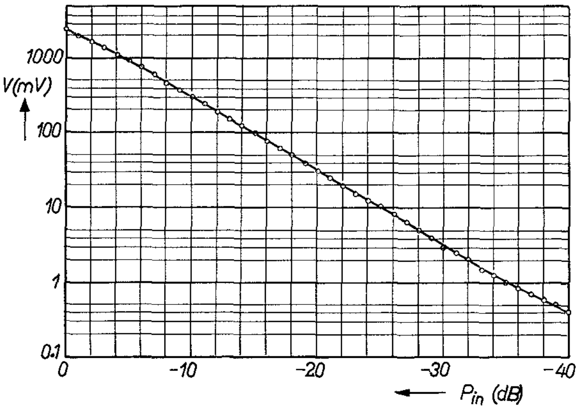

Fig. 5. The equation $\Delta V \sim P$ is satisfied. The experimental conditions are $l=4$ mm, $p=11$ Torr in Ne, $V_0 \approx 150$ V, $i_0 \approx 17$ mA, $\lambda=4$ mm and $P_0=120$ mW corresponding to 0 dB.

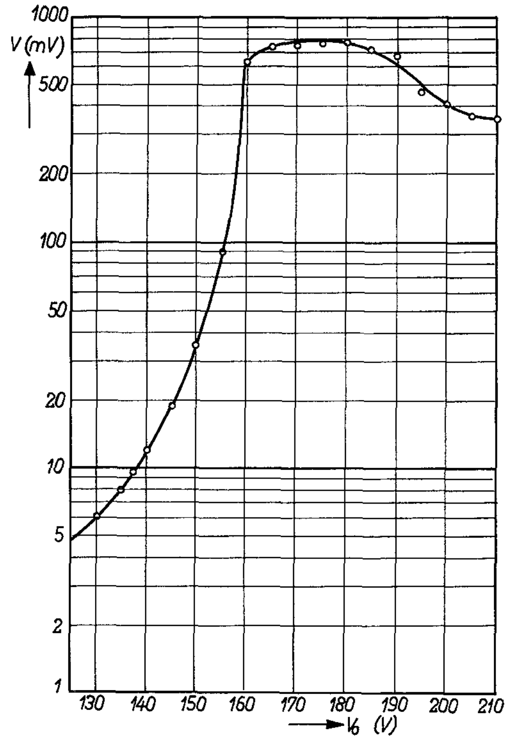

Fig. 6. The rectified current as measured over a resistance $R_v=5$ kΩ, as a function of the applied potential, which is proportional to the reduced plasma frequency ω_p/ω. The current is approximately linearly related to this potential with a differential resistance $R_i=9$ kΩ; Ne $p=9$ Torr, $\lambda=2$ mm, $l=2$ mm.

The impedance of the detector is such that only relatively small reflections occur: the field is more or less matched by the glass point and envelope. It is important to realize that the detection mechanism is a volume effect and thus the detector can form a matched termination to the waveguide. This implies also that the output can be frequency-independent apart from the dependence which arises from the physics of the detection mechanism which is slightly dependent on the frequency. The gas discharge detector is essentially a HF wide-band device.

A disadvantage of our detector is its intrinsic relatively long response time, which is of the order of 10^{-5} sec. Microwaves modulated with a 50 kc/s signal could be detected without decrease in performance. In this sense our detector is a LF narrow-band device.

As has been said in Section I, the theory on microwave detection with a gas discharge detector is based on the electronic and ionic processes which take place in the cathode fall. Apart from the evidence for this theory as extensively discussed in the earlier paper mentioned, it was found here again that the output of a coaxial electrode arrangement is much higher than that of a plane electrode arrangement. Furthermore, as with 3 cm waves, the rectified potential with 4 mm waves shows a maximum as a function of the applied potential V_0 or, because of (1), of the relative plasma frequency ω_p/ω (Fig. 6). A similar though still less sharp maximum is found with 2 mm wave detection.

Because these measurements have been done with a thin pin cathode ($\phi \approx 200$ μ) the theory which, as said, has been given for plane electrodes [17], cannot be applied as it stands; nevertheless, we feel that the existence of detected voltage maxima is in accordance with it.

IV. The Noise Behavior of a Gas Discharge Used as a Synchronous Detector

In this section it will be shown that the detector can be usefully applied in a synchronous detection circuit. Now, due to the large dynamic range of the detector, a high power local oscillator can be applied to reduce the noise level. The modulation frequency of the signal to be measured can be 50 kc/s. For higher modulation frequencies the performance degrades due to the LF response time of the gas discharge.

The circuit shown in simplified form in Fig. 7 has been used to investigate the noise level of the synchronous detector. In Fig. 7 the HF power of the klystron (1) is divided by the directional coupler (2). The HF power P_{HF} in branch a, LF modulated by the PIN modulator (3) and attenuated by the calibrated attenuator (4), forms the signal to be measured. The HF power P_{lo} in branch b simulates local oscillator power. With the phase shifter (6) the local oscillator output phase can be adjusted to maximize the LF output signal of the detector. This LF signal is amplified, rectified by the phase-sensitive detector (7) and registered on a recorder. Of course, there is no difference between coherent and incoherent mixing as long as the measurement time is long with respect to the difference frequency period.

The NEP of the detector has been measured and compared with that of the synchronous detection circuit.

In order to measure the NEP of the detector, the local oscillator power is set at zero. The results are shown in Fig. 8, record 1. The NEP turns out to be about 9.10^{-7} W at 1 c/s bandwidth; this voltage noise level agrees with the results at 50 kc/s bandwidth mentioned in Section III. In Fig. 8, record 2, the NEP of the synchronous detector is shown at a local oscillator power P_{lo} of 80 mW. The NEP has been decreased to a value as low as 10^{-11} W at 1 c/s bandwidth in this arrangement.

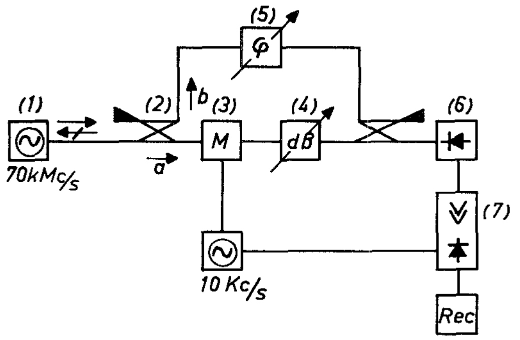

Fig. 7. The simplified circuit for measuring the NEP of the synchronous detector. The high frequency is equal to 70 kMc/s, the modulation frequency is 10 kc/s and the modulation depth is 0.5.

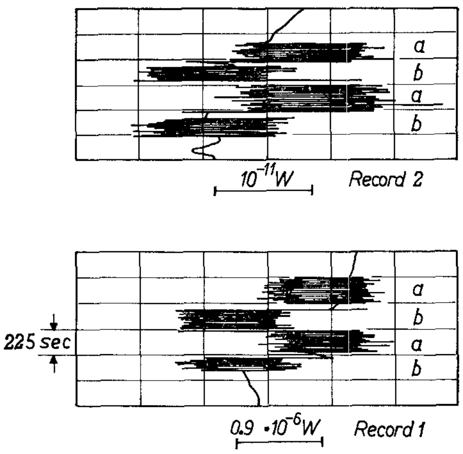

Fig. 8. Record 1 shows the NEP of the detector, record 2 shows the NEP of the detector in a synchronous detection circuit for P_{lo} = 80 mW. In the periods a and b the NEP has been recorded with and without the signal to be measured, respectively.

Finally, a rough calculation of the NEP of the gas discharge detector in a synchronous detection circuit will be given here. The PIN modulator causes an amplitude modulated signal according to

$$E_{\mathrm{HF}} = \hat{E}_{\mathrm{HF}}(1 + a \cos pt) \cos \omega t, \tag{4}$$

at least to a first approximation.

Here a is the depth and p the frequency of the modulation.

Rectifying the HF signal, harmonics of the modulation frequency may be excited, but only the fundamental component V_1 is interesting, and the other components are not amplified and detected, hence $V_1 = V$.

It can be shown that in case of zero local oscillator power the rms value of the fundamental component of the detector output is equal to

$$(V_1)_{\mathrm{rms}} = 1.4a\gamma P_{\mathrm{HF}}. \tag{5}$$

Using the detector in a synchroneous detection circuit the rms value of this component will be

$$(V_1)_{\mathrm{rms}} = 1.4a\gamma\sqrt{P_{\mathrm{HF}} \cdot P_{lo}}. \tag{6}$$

as long as $P_{lo} \gg P_{\mathrm{HF}}$.

The noise power originating in the local oscillator can be neglected, because that of the gas discharge is dominant even at a microwave power level as high as 100 mW. By comparing the noise levels in records 1 and 2 this can easily be verified. Denoting by P_n the NEP of the detector, by P_m the NEP of the same in a synchronous detection circuit and by V_n the noise level, we can derive from (5) and (6) the equation

$$V_n = 1.4a\gamma P_n = 1.4a\gamma\sqrt{P_{lo} \cdot P_m}. \tag{7}$$

Hence we find under the above-mentioned conditions

$$P_m = \frac{P_n^2}{P_{lo}}. \tag{8}$$

From (8) it can be seen that in order to obtain a low P_m the local oscillator power P_{lo} should be high.

In our measurements of the NEP of this detector we used $P_{lo} = 80$ mW. For $P_n = 9.10^{-7}$ W the NEP of the circuit should be 10^{-11} W. This result, discussed at the beginning of this section, agrees very well with the measured result.

In general a gas discharge has excessive noise, but, because of the wide dynamic range of the detector, a high local oscillator power can be applied to reduce the NEP. In a synchronous detection circuit the wide dynamic range has been exploited.

V. Conclusions

The gas discharge detector in a ZA tube filled with Ne at a pressure of about 100 Torr has the following characteristic features.

1. It is very rugged, can withstand mechanical shocks, high power bursts and thermal overloading. Hence, it can be used effectively for mm wave antenna pattern measurements.
2. The responsivity γ is of the order of 50 V/W; occasionally samples showing $\gamma \approx 200$ V/W can be sorted out. The internal impedance is low: $R_i \approx 3$ kΩ.
3. The high noise power level limits the minimum detectable signal to about 5 μW at 50 kc/s bandwidth; this can further be reduced by narrow-band LF detection.
4. The time constant of the detector is about 10^{-5} sec which settles the 3 dB point to about 50 kc/s.
5. The responsivity is constant over an incident power range of about 30 dB.
6. The detector has these characteristics in a HF wideband arrangement.
7. The detector has a low reflection coefficient and needs no matching components in principle.
8. The detector can be relatively cheap; its use as a monitor is therefore recommended.
9. In a synchronous detection circuit the NEP can be as low as 10^{-11} W at 1 c/s bandwidth.
10. The same tube can be used for efficient 4 or 2 mm wave detection; only the applied voltage should be increased.
11. For the time being, no arguments can be put forward against the prospect of successful operation of this kind of detector in the 1 mm or sub-mm range especially if performance could be raised by making an integrated component.

Acknowledgment

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Corrections

The following has been called to the attention of the Editor.

Charles W. Steele, "A Nonresonant Perturbation Theory," Vol. MTT-14, pp. 70–74, February 1966.

Equation (35) applies only to linearly polarized electric and magnetic fields at the point of perturbation. (This restriction was not stated.) Equation (34) is, however, more general and applies to the elliptically polarized waves as well.

Edward G. Cristal, "Band-Pass Spurline Resonators" (Correspondence), Vol. MTT-14, pp. 296–297, June 1966.

Equation (3) should have read

$$D = \frac{Y_{oo}{}^{a} - Y_{oe}{}^{a}}{2} = \frac{Y_{oo}{}^{b} - Y_{oe}{}^{b}}{2}. \quad (3)$$

Figures 1 and 2, as follows, should have appeared in place of the ones printed.

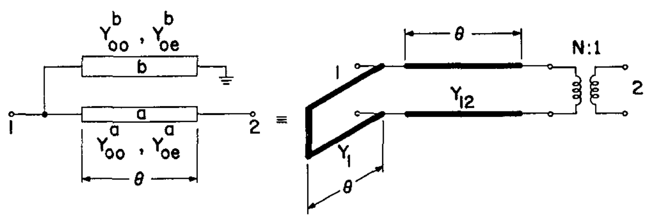

Fig. 1. Band-stop spurline resonator and its open-wire-line equivalent network.

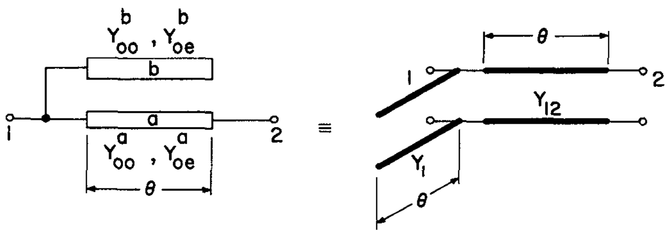

Fig. 2. Band-pass spurline resonator and its open-wire-line equivalent network.