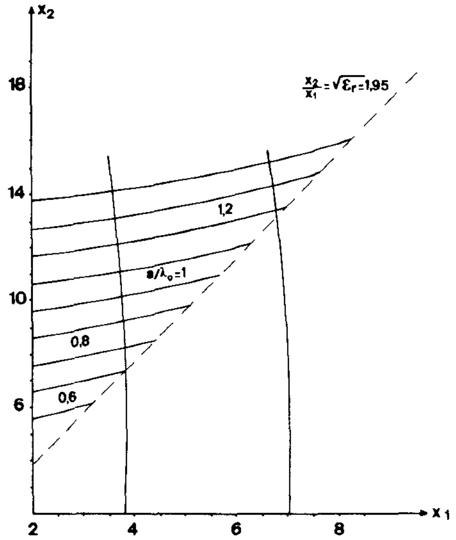

Fig 2 Graphical resolution for the propagation constant β. Experimental conditions: $a/\lambda_0 = 1$

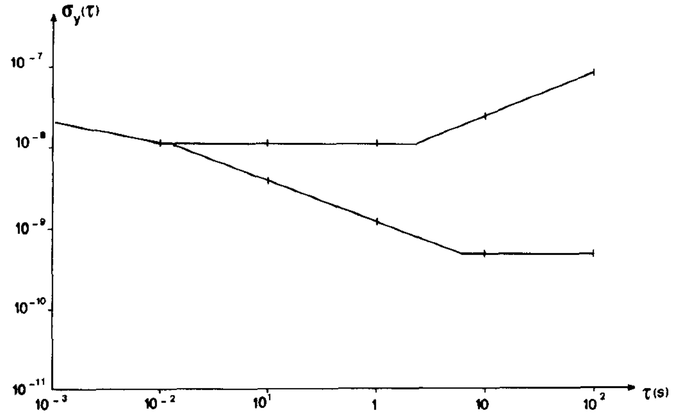

Fig. 3. Allan variance $\sigma_y(\tau)$ for free and frequency locked oscillator at 468 MHz.

where β is the unknown propagation constant, a and b are outer and inner radii of the quartz tube, and ϵ_r is the tube permittivity.

Equations (1) and (2) may be solved graphically. In Fig. 2, two families of curves are plotted: a) nearly vertical curves give the values of x_1 and x_2 which obey to (1); and b) the sections of hyperbolas are the loci of a point whose coordinates (x_1, x_2) verify (2), depending on the ratio a/λ_0.

With the numerical values $\epsilon_r = 3.78$ and $b/a = 0.92$, only the TE_{01} mode can propagate in that guide if

$$0.6 < a/\lambda_0 < 1.07.$$

With an outer quartz tube radius of 12.5 mm, the cutoff frequency of the two first modes TE_{01} and TE_{02} are 14.4 and 25.8 GHz, respectively. Thus, in the experimental conditions where $a/\lambda_0 \simeq 1$, the cell behaves like a monomode helix waveguide for the TE_{01} mode with phase velocity of the order of 3.75×10^8 m/s.

A plot of the frequency stability obtained for the frequency-locked oscillator with the closed ammonia cell described above is shown in Fig. 3. These data were computed using the so-called Allan variance for averaging times varying from 10 ms to 300 s; the frequency drift has not been removed. The flicker floor is found at 5×10^{-10} for τ less than a few minutes.

Fluctuations of the ammonia molecules excitation power limit the long term stability to 8×10^{-10} over a day at this time.

Conclusion

A closed absorption cell has been developed for the use in two fundamental areas: passive frequency standards and spectroscopy. The good performances of that type of cell as a monomode waveguide with small insertion losses make it very attractive for microwave frequencies (from 10 to 100 GHz).

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94-GHz 4-Port *E*-Plane Junction Circulator

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***Abstract*—A 4-port junction circulator for use in 94-GHz *E*-plane integrated circuits is investigated. The design incorporates an *E*-plane *X*-junction of standard metal waveguides with a single ferrite disk on one of the narrow walls of the junction plus a metal plunger extending into the junction from the opposite side. The plunger is used to tune the $n = 0$ mode to the circulator center frequency and additionally can be used to tune the circulator center frequency over several gigahertz without critically degrading circulator performance. Minimum insertion loss of 0.65 dB was typical in a series of 12 plunger-tuned circulators with adjacent port isolation better than 20 dB, and crossport isolation better than 15 dB over nearly a 1-GHz bandwidth.**

I. Introduction

Printed *E*-plane integration of millimeter-wave circuits has made great progress recently [1] and *Y*-junction circulators have been developed especially to serve in *E*-plane circuits [2]. In this paper, the 4-port circulator is presented as another variant of the *E*-plane junction circulator. 4-port circulators may be employed as a transmit–receive duplexer with one of the ports terminated in a matched load to absorb the power reflected from the receiver-protection circuit during transmission. This is not the only useful application of the 4-port circulator, as other applications have been identified, e.g., in power-combining, and will be reported later.

At present, *E*-plane 4-port circulators seem to have not found widespread use, probably due to the limited bandwidth that has restricted use of *E*-plane *Y*-junction circulators. Consequently, only two publications on the subject have been found [3],[4], describing devices for high average power applications, where *E*-plane circulators have a clear advantage.

II. Port Circulator Design

Similar to H-plane 4-port junction circulators [5], a phenomenological description of E-plane devices employs three resonance modes present in the waveguide junction, namely the $n = \pm 1$ modes and the $n = 0$ mode. The former modes are the split rotating modes that perform the circulation action in Y-junction (3-port) circulators [6], and the $n = 0$ mode is an additional mode necessary only in the 4-port circulator. To adjust the resonant frequency of the $n = 0$ mode to the circulator center frequency, in the published circulator designs [3],[4], dielectric top-loading of the ferrite disks is employed. This approach has been tried in the realization of circulators for the 90-GHz band. It has been found that, in order to achieve proper circulation, a delicate balance of ferrite disk height and dielectric loading configuration has to be found.

In an attempt to circumvent this problem, an alternative solution was investigated. In the 4-port circulator design developed, only one ferrite disk is used on one narrow side of the waveguide junction and a metal plunger is used as a tuning element for the $n = 0$ mode, as shown in Fig. 1. Since there appears to be no investigation available in the literature concerning the nature of the $n = 0$ mode in E-plane 4-port circulators, we are left to speculate. A logical choice would be a circular-symmetric TM_{01}-mode characterized by circular electric fields in the E-plane of the junction and a zero electric-field strength in the center. Such a field distribution would only weakly be perturbed by a metal rod in the center symmetry axis, unless a relatively thick plunger is used. On the other hand, the plunger is directed perpendicular to the TE_{10}-waveguide modes of the connecting waveguide arms and, thus, the perturbation of these fields also is small.

In the following, the results of experimentation with the 4-port circulator construction of Fig. 1 are given first for a circulator without a plunger. Using a standard waveguide (WR-10) E-plane junction and a circular ferrite disk (AEG-Telefunken Nickel–Ferrite RF-10, $\epsilon_r = 14.4$, $4\pi Ms = 5000$ G) of 1.8-mm diam ("natural" diameter of the junction, that is, the maximum diameter which would fit into junction) and 0.26-mm height, circulator characteristics were found as plotted in Fig. 2. It can be seen that, in terms of scattering parameters, insertion loss ($|S_{21}|$) is about 0.8 dB near 94 GHz, but optimum input match ($|S_{11}|$) and maximum isolation to ports 3 and 4 ($|S_{31}|$ and $|S_{41}|$) are centered at widely varying frequencies. Also, it has to be noted that the isolation of port 3 in the vicinity of 94 GHz stays far below the 15-dB level. The relatively high insertion loss, the incongruent behavior of the three other scattering coefficients, and the very low isolation of port 3, all together, are symptomatic of a failure in proper tuning of the $n = 0$ mode in the circulator junction.

The use of a metal plunger as depicted in Fig. 1 has been found to be a very practical means to achieve such tuning. It was found that the diameter of the metal rod should be at least 0.4 mm for circulators operating in the 90-GHz band.

Smaller diameters did not yield sufficient perturbation of the ferrite disk modes. Also, it was observed that the rod has to be brought near the ferrite disk to be of any influence on the circulator characteristics. Both observations confirm our picture of the field distribution of the $n = 0$ resonance mode, namely that it has zero electric field in the center symmetry axia and that it is, like the $n = \pm 1$ modes [6], strongly concentrated in or near the ferrite disk.

A plot of the circulator characteristics of a plunger-tuned 4-port circulator with an optimum ferrite height of 0.22 mm is shown in Fig. 3. It is seen that the insertion loss at around 94 GHz is reduced to about 0.65 dB, which is only some 0.15 dB higher than the loss in a comparable 3-port Y-junction circulator [2]. Also, it is found that the isolation of ports 3 and 4 and the input match are optimum at about the same frequency. Isolation of port 3, however, still is not satisfactory, not even achieving the 20-dB level. Phenomenologically, it may be argued that, in this example, the second condition for circulation is not perfectly fulfilled, namely that the amplitudes of the resonance modes are equal at the four ports. About 0.1 dB of insertion loss is because of the nonideal isolation of port 3.

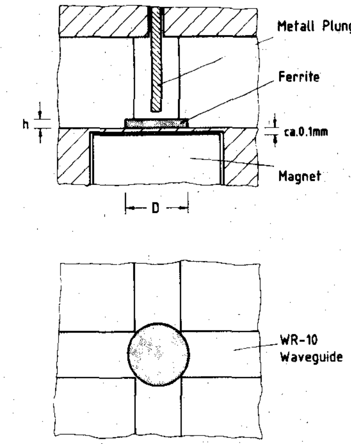

Fig. 1. Cross-sectional view of plunger-tuned 4-port circulator.

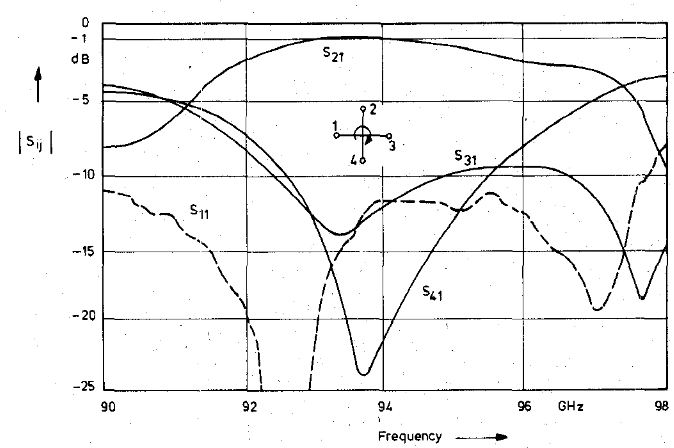

Fig. 2. Scattering coefficients of 4-port circulator without plunger tuning.

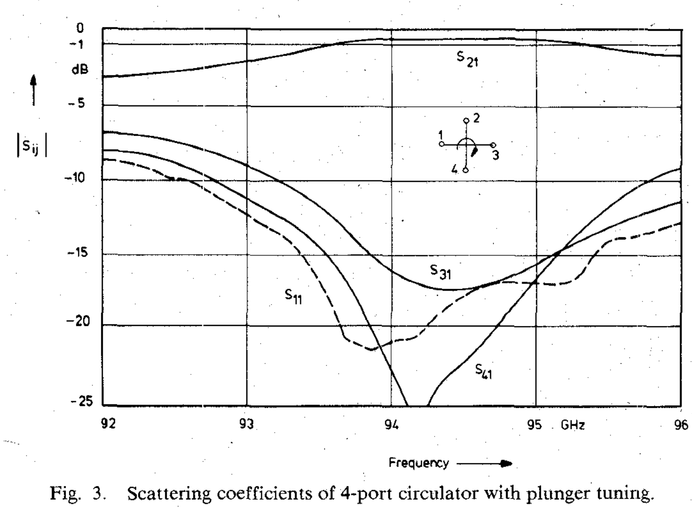

Fig. 3. Scattering coefficients of 4-port circulator with plunger tuning.

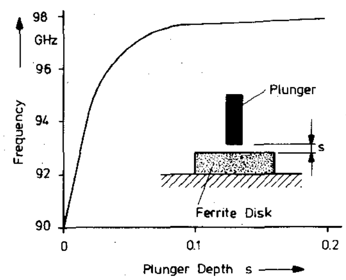

Fig. 4. Circulator center frequency as a function of gap width between plunger and ferrite disk.

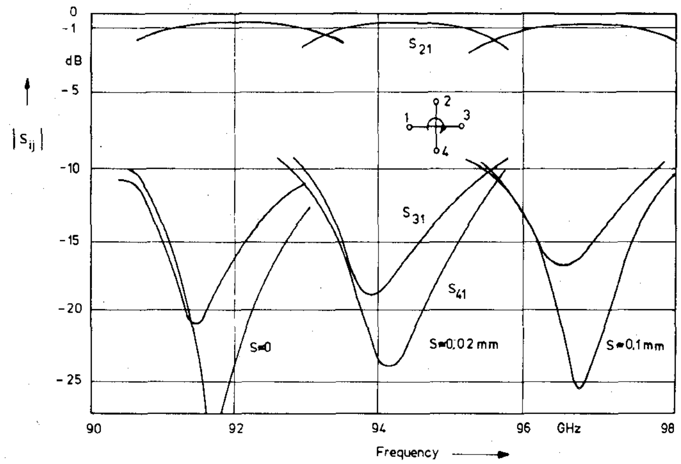

Fig. 5. Scattering coefficients of 4-port circulator with plunger at three different adjustments.

The characteristics plotted in Fig. 3 have been measured with the plunger only some 1/100 mm above the ferrite disk. It is interesting to note that, by further reducing the height of the plunger, the frequency of circulation can be tuned over an extremely broad range. The dependence of circulator frequency and spacing of the plunger and ferrite disk is sketched in Fig. 4. It is seen that, for gaps from zero to about 20 μm, a shift of frequency occurs from 90 to about 95 GHz. For larger gaps, the slope decreases to asymptotically approach the circulator frequency of the untuned circulator. For three different adjustments of the plunger, the circulator characteristics have been recorded in Fig. 5. It is seen that the basic properties of the 4-port circulator are not critically degraded by the variation in plunger depth. The magnetic bias, in all cases, was the same at about 0.2–0.3 T (2–3 kG) which is considerably higher than in 3-port devices of comparable bandwidth. A stack of two to three 4-mm diam by 1.5-mm height rare earth magnets was used to achieve proper bias. Two things can be concluded from these observations. Firstly, the functional dependence of the curve in Fig. 4 indicates that the resonance fields in the junction are exponentially decaying from the top surface of the ferrite disk, which is a normal property of dielectric resonators. Secondly, from the fact that the plunger tunes the center frequency of the circulator, it has to be concluded that the plunger not only perturbs the $n = 0$ mode, but the $n = \pm 1$ modes are affected also. Furthermore, the tuning sensitivity $\Delta f / \Delta s$ of the modes seems to be practically the same, so that only little deterioration of the circulator characteristics occurs due to the tuning. The concluded tuning of the $n = \pm 1$ modes was tested in a separate Y-junction circulator using the same plunger in the junction center as was used in the 4-port experiments. It was found that the frequency of circulation in the Y-junction circulator indeed could be varied by approximately the amount that has been found in the 4-port circulators. The circulator input match and isolation was, however, degraded by the plunger so that tuning would only be useful in a very restricted range where the plunger penetrates very little into the waveguide junction ($s > 0.2$ mm).

III. Conclusions

The design of a 4-port circulator for millimeter-wave frequencies has been investigated. A metal plunger is used to tune both the $n = 0$ mode and the $n = \pm 1$ modes. Wide mechanical tuning of the circulator center frequency is achieved without critical degradation of the circulator properties. In the production of a small series of 12 circulators for 94 GHz, the plunger has been used to tune the ciculators to exactly the same center frequency in a very simple way, without the need to individually adjust the ferrite disk height or the magnetic bias, as would be necessary if a dielectric configuration were used.

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