A NARROW-BAND MILLIMETER-WAVE Y-JUNCTION CIRCULATOR WITH WIDE-BAND TUNING CAPABILITY

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Abstract

This paper describes the mode of operation and the synthesis technique for a series of narrow-band tuneable circulators suitable for use in millimeter-wave system channel applications. Typical design and performance data are presented for circulators operating from 50 to 110 GHz.

Introduction

In 1959, Auld showed that a mutual 120° phase difference between the three scattering matrix eigenvalues is the necessary and sufficient condition for a lossless symmetrical three-port junction to be a circulator[1]. The phase-frequency characteristics of these eigenvalues provide a means of identifying modal resonances within such a junction, and the knowledge of these resonances is important to the design of Y-junction circulators.[2,3] This paper will review the eigenvalue analysis of symmetrical 3-port junctions, describe an eigenvalue measuring circuit and present X-band data illustrating the identification of internal field modes in a Y-junction. An example of the use of these modes in the synthesis of a tuneable X-band circulator will be given together with considerations for scaling the device into the millimeter-wave range.

Eigenvalue Analysis

The eigen-solutions for the scattering matrix [S] of a symmetrical Y-junction are given by

$$[S]\ [x]_i = \phi_i\ [x]_i \tag{1}$$

where $[x]_i$ are the eigenvectors and ϕ_i are the eigenvalues[1]. In physical terms $[x]_i$ represent a set of three excitations of equal amplitude applied simultaneously to each of the three ports of the junction. The eigen-excitations are

$$[x]_1 = \frac{1}{3}\begin{bmatrix}1\\1\\1\end{bmatrix} \quad [x]_2 = \frac{1}{3}\begin{bmatrix}1\\1e^{+j120°}\\1e^{-j120°}\end{bmatrix} \quad [x]_3 = \frac{1}{3}\begin{bmatrix}1\\1e^{-j120°}\\1e^{+j120°}\end{bmatrix} \tag{2}$$

They are distinguishable from one another by the relative phases of the signals applied at each of the three ports. $[x]_1$ is the in-phase excitation with the signals in each port having equal magnitude and phase. $[x]_2$ and $[x]_3$ are the clockwise and anticlockwise rotating excitations respectively with the signals in each port having equal magnitudes but differing in phase by 120°. Equation (1) states that for excitation $[x]_i$ the reflected signal at each port equals the incident signal times ϕ_i. In other words, ϕ_i is the reflection coefficient for the corresponding eigen-excitations $[x]_i$. If the junction is lossless, conservation of energy requires the eigenvalues to have unity amplitude. They are then distinguishable from one another in phase only. The simultaneous application of the three excitations is equivalent to exciting port 1 only, i.e.,

$$\sum_{i=1}^{3} [x]_1 = \begin{bmatrix}1\\0\\0\end{bmatrix}. \tag{3}$$

The output from the junction under this condition is

$$\text{Output} = \sum_{i=1}^{3} \phi_i\ [x]_i. \tag{4}$$

From equations (2) and (4) it can be seen that for $\phi_1 = 1$, $\phi_2 = 1\ \exp(-j120°)$ and $\phi_3 = 1\ \exp(+j120°)$

$$\sum_{i=1}^{i=3} \phi_i\ [x]_i = \begin{bmatrix}0\\1\\0\end{bmatrix}. \tag{5}$$

Equations (3) and (5) describe circulation from port 1 to port 2. The requirement for circulation, therefore, is that the eigenvalues be mutually phase displaced by 120°, i.e., $\angle\phi_2 - \angle\phi_1 = \angle\phi_3 - \angle\phi_2 = \pm 120°$. The problem of providing circulation is then one of adjusting the eigenvalues for the correct phase displacement. To do this the frequency dependence of the eigenvalues must be examined.

Eigenvalue Measurement

The most direct approach to the measurement of the eigenvalues is to apply each eigen-excitation in turn and to measure the reflection coefficient on any one port of the junction. Fig. 1 shows a block diagram of a circuit used for this purpose. The 3-way power divider couples signals of equal magnitude to each circuit branch. Each branch is identical and consists of standard X-band waveguide components. The 20 dB attenuators are used to minimize unwanted reflections and the variable attenuators to equalize signal levels in each branch. The phase shifters are used to set the relative phases for the three eigen-excitations. To avoid placing two couplers in each circuit branch, the incident signal is sampled at port 1 and the reflected signal sampled at port 2. This results in flat phase errors of ±120° in $\angle\phi_2$ and $\angle\phi_3$. The error is removed by flat offsets of ∓120° in the phase gain indicator. The following are a few typical results obtained with this set. Fig. 2 shows the eigenvalues for a junction with a full height ferrite cylinder. The rapid 360° phase shift in ϕ_2 and ϕ_3 indicates a resonator in the equivalent circuit for the junction. The resonance in this case is the diametric $TM_{\pm 1,1,0}$ mode normally associated with circulation. This can be determined from the diameter and material parameters of the ferrite cylinder. The dashed line shows the degenerate resonance for the $TM_{\pm 1,1,0}$ mode with zero magnetic biasing field. When the ferrite is partial height, transverse electric fields are generated at the dielectric-ferrite interface at the end of the ferrite cylinder. These fields couple to the axial $HE_{\pm 1,1,n+\delta}$ modes which resonate along the length of the ferrite rod. If the ferrite rod is in contact with one wall of waveguide junction and separated from the other by a dielectric spacer, the resonances occur when the ferrite is an odd number of quarter-wavelengths long, i.e., n = 0,1,2... and $\delta \approx 0.5$. If the ferrite is separated from both walls by dielectric spacers, the resonances occur when the ferrite is an integral number of half-wavelengths long, i.e., n = 0,1,2... $\delta \approx 1$. The dielectric constant of the spacers must differ significantly from the dielectric constant of the ferrite for the coupling to the $HE_{\pm 1,1,n+\delta}$ modes to be effective. Fig. 3 shows the eigenvalues for a junction with a partial height ferrite cylinder. Resonances of both the $TM_{\pm 1,1,0}$ and $HE_{\pm 1,1,n+\delta}$ types are present. There are no in-band resonances in $\angle\phi_1$ in either Figs. 2 or 3, and the slope of $\angle\phi_1$ does not match those of $\angle\phi_2$ and $\angle\phi_3$. Because of the different slopes, the 120° phase separation between ϕ_1, ϕ_2 and ϕ_3 exists only over a very narrow band. One way of equalizing slopes is to introduce resonances into ϕ_1. The electric field at the junction center is a maximum for the $[x]_1$ eigen-excitation, and a metallic conductor (pin) placed on the junction symmetry axis can be used to induce resonances in ϕ_1. The pin may be in contact with one wall of the junction and inserted within the ferrite. The pinned ferrite then acts as a Goubau line and $TM_{0,1,n+\delta}$ resonances are induced in ϕ_1 when the pin is an odd number of quarter-wavelengths long, i.e., n = 0,1,2... and $\delta \approx 0.5$. The pin may also form the center conductor of a coaxial resonator recessed in the broad wall of the waveguide junction. The coaxial resonator may be a quarter-wave resonator short-circuited on one side or a half-wave resonator open circuited on both sides. Fig. 4 shows the eigenvalues for a pinned ferrite with $TM_{0,1,n+\delta}$ resonances in ϕ_1.

Circulator Synthesis

The magnetic fields for the $TM_{+1,1,0}$ and $TM_{-1,1,0}$ resonances are circularly polarized at the junction center. Since these fields rotate in opposite directions they are presented with different permeabilities by a magnetized ferrite, and the resonances in ϕ_2 and ϕ_3 are separated in frequency as shown in Fig. 2. The frequency splitting results in appreciable phase separation of ϕ_2 and ϕ_3 only in the region between the resonances. Since circulation requires $\angle\phi_3-\angle\phi_2$ and $\angle\phi_2-\angle\phi_1$ to be ±120°, circulation is practical only in the vicinity of these resonances. The bandwidth available for circulation depends on the loaded Q-factor, Q_L, of these resonances. As Q_L decreases the resonances get broader, a larger permeability difference and frequency splitting is required to achieve 120° phase separation, and a larger bandwidth is available for circulation. Since broad bandwidth is a normal requirement in circulator designs, Q_L is made small by strongly coupling the external fields to the ferrite resonator. This is usually achieved by heavily loading the resonator with dielectric spacers and a quarter-wave transformer. The permeability difference for the rotating modes is proportional to the ferrite saturation magnetization and inversely proportional to frequency. To maintain a constant fractional bandwidth as frequency is increased, the saturation magnetization must be scaled with frequency. A practical $4\pi M_s$ limitation of 5,000 Gauss prevents this scaling from being carried out above approximately 30 GHz. To achieve the 120° phase separation in the millimeter-wave range, the Q-factor of the resonance must therefore be increased, and this leads to the prediction of narrower bandwidths for circulation. However, it is now clear that additional rotating mode resonances are present in a junction with partial height ferrite. If these resonances are staggered in frequency, the phase separation can be arranged to span two or more modal resonances greatly increasing the band over which circulation is possible. The phase adjustment for ϕ_2 and ϕ_3 is accomplished by varying the magnetic biasing field. The phase adjustment for ϕ_1 may be achieved by the inclusion of resonant elements such as the axial pin described earlier. If the resonant element is externally adjustable, $\angle\phi_1$, $\angle\phi_2$ and $\angle\phi_3$ may be tuned for circulation at any frequency over a substantial portion of the band covered by the staggered resonances in $\angle\phi_2$ and $\angle\phi_3$. Since the RF magnetic field is zero at the junction center for eigen-excitation $[x]_1$, a change in biasing field leaves ϕ_1 undisturbed as shown in Fig. 3. Likewise, since the RF electric field is zero at the junction center for eigen-excitations $[x]_2$ and $[x]_3$, the pin adjustment does not affect ϕ_2 and ϕ_3 as shown in Fig. 4. The independent nature of these adjustments considerably simplifies the tuning procedure for the circulator.

Experimental Results

Circulators were designed by X-band which could be scaled into the WR-15 (50 to 75 GHz) and WR-10 (75 to 110 GHz) bands where the waveguide dimensions are 0.075 x 0.150 inches and 0.050 x 0.100 inches respectively. Scaling factors of six and nine were chosen so that the X-band waveguide size was 0.450 x 0.900 inches. To obtain circulators with similar characteristics at different frequencies, the ferrite saturation magnetization and biasing field must be scaled. Assuming a nickel-zinc ferrite with a saturation magnetization of 5,000 Gauss for the millimeter-wave devices, the saturation magnetizations of the ferrites for WR-15 and WR-10 prototypes at X-band were chosen to be 800 Gauss and 500 Gauss respectively. Simple resonant structures were constructed to insure that the ferrite dielectric constants were identical. Since the maximum achievable biasing field with a reasonably sized magnet on one side of a millimeter wave junction was approximately 900 oersted, the limitation on biasing field for the WR-15 and WR-10 prototypes at X-band was set at 150 and 100 oersteds respectively. Fig. 5 shows a cross-section of a typical circulator design. The ferrite cylinder dimensions were selected to stagger a $TM_{\pm 1,1,0}$ and $HE_{\pm 1,1,1+\delta}$ resonance in ϕ_2 and ϕ_3. The Q-factor of these resonances was adjusted to maximize the band over which $\angle\phi_2\angle\phi_3$ was displaced by at least 120° with the biasing field available. This involved the use of a quarter-wave transformer for the WR-15 prototypes. At any frequency within this band, $\angle\phi_2-\angle\phi_3$ could then be set to exactly 120° with a simple magnet adjustment on one side of the junction. A half-wavelength resonator was selected for adjusting the phase of ϕ_1. This type of resonator was considered superior since it avoided the use of adjustable coaxial short circuits and drilled ferrites both of which are mechanically difficult to realize in the millimeter-wave range. The center conductor (pin) was supported with a rexolite sleeve, and the coax outer diameter was made small enough to eliminate any RF leakage above the pin. The pin travel was restricted to the region between the ferrite and the broad wall of the waveguide junction. Seven circulators of this kind were designed at X-band and scaled into the millimeter-wave range. The results on the three circulators for the WR15 (50-75 GHz) band are shown in Fig. 6. The pin and biasing field adjustments permit the isolation and return loss of each circulator to be peaked at any frequency within its tuning range. Four circulators were required to cover the WR10 (75-110 GHz) band. The tuneable bandwidth varied from 22% at 50 GHz to 7.5% at 110 GHz. The insertion loss varied from 0.25 dB to 0.65 dB (a 0.5 dB limit appears feasible by increasing the number of design codes from 7 to 8), and the instantaneous bandwidth measured at the 30 dB isolation and return loss level was in the range 500 MHz to 1 GHz.

Conclusions

The measurement of the eigenvalue phase-frequency characteristics has been shown to be a powerful tool for identifying RF field modes in ferrite-loaded waveguide Y-junctions. The knowledge gained from the control of these modes by the physical structure has been used to design a series of tuneable circulators operating from 50 to 110 GHz. Since these devices may be tuned for high performance at any frequency within this range, they should prove useful in millimeter-wave system channel applications.

Acknowledgments

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References

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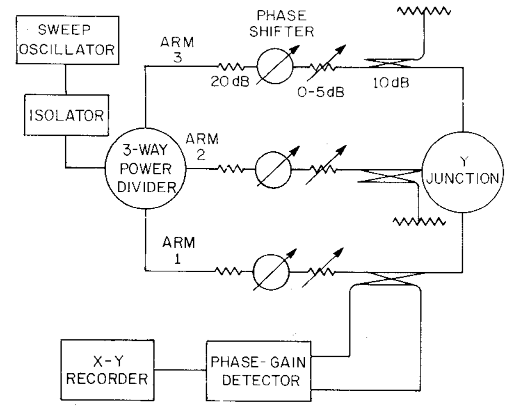

Fig. 1 Eigenvalue measuring set

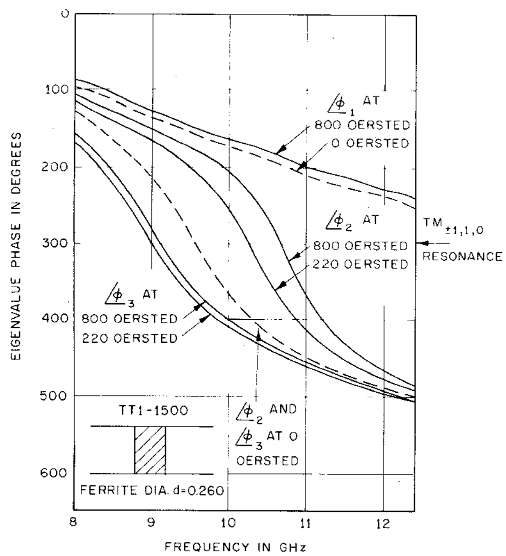

Fig. 2 Eigenvalue phase with a full height ferrite

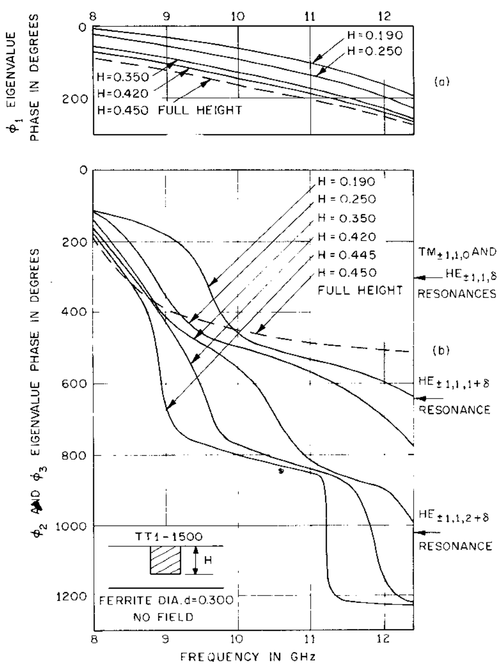

Fig. 3 Eigenvalue phase with a partial height ferrite

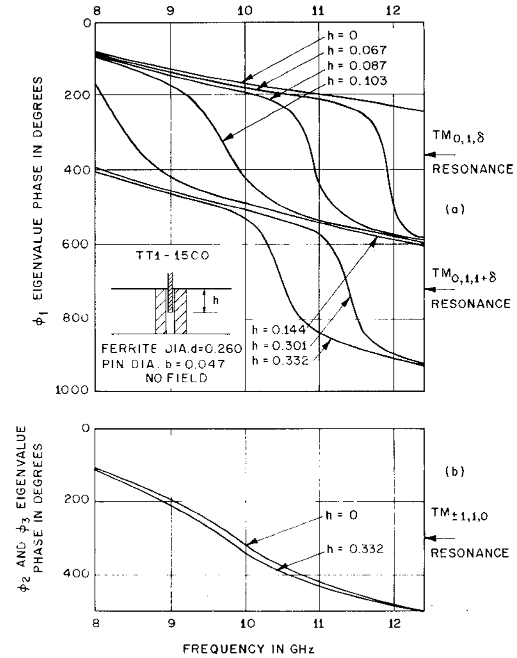

Fig. 4 Eigenvalue phase with a pinned ferrite

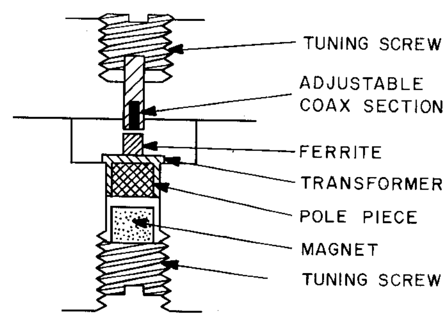

Fig. 5 Cross-section of a typical tuneable circulator

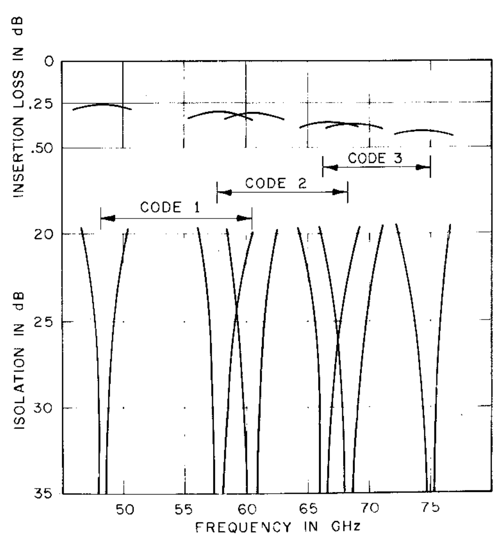

Fig. 6 Characteristics of the WR-15 tuneable circulators