# III-4 A NEW TYPE OF LATCHING, SWITCHABLE, FERRITE-JUNCTION CIRCULATOR

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For a long time, ferrite-junction circulators required an externally applied dc magnetic field provided by either permanent magnets or electromagnets.[1,2] Recently, significant progress has been made in the development of switchable, latching, single-junction, ferrite circulators in waveguide[3,4,5] and stripline circuits.[6]

This paper presents approximate theoretical results and initial performance data on a new type of circulator[5], a three-port, strip-line, latching, switchable circulator illustrated schematically in Fig. 1. This circulator employs two latched ferrite elements placed between a central conductor and two ground planes. Each element provides a closed magnetic path through the ferrite cylinder and ring, and two ferrite or high-remanence metal discs. The ferrite operates at remanence after passage of a direct current pulse. Switching (i.e., reversal of transmitting and isolating ports) is achieved by reversal of the polarity of the pulse.

The novelty of this design is the placement of the entire dc magnetic circuit within the region of circulation, and achievement of this circulation by use of cylinder-and-ring assemblies having opposite directions of dc magnetizations. These features permit a very compact design, and provide fast switching time (approximately two microseconds) and low switching energy (tens of microjoules in the microwave region).

The results of an approximate theoretical analysis, performed by a method similar to that described by Bosma[1] and Fay and Comstock[2], for negligible thickness of the non-magnetic gap shown in Fig. 1, are as follows:

The resonance split of the transverse electric (TE) modes can be obtained from the following equation:

$$\left[J'_n(x_2) \pm \frac{\kappa n}{\mu x_2} J_n(x_2)\right]\left[1 \pm \frac{\pi \kappa n}{\mu} J_n(x_1)\, Y_n(x_1)\right] \mp \frac{\pi \kappa n}{\mu} J_n^2(x_1)\left[Y'_n(x_2) \pm \frac{\kappa n}{\mu x_2} Y_n(x_2)\right] = 0 \qquad (1)$$

where n is a positive integer, $J_n$ and $Y_n$ denote the Bessel functions of order n of first and second kind respectively, $x_1$ and $x_2$ are respectively the normalized[7] inner and outer radii of the ferrite ring, and K and $\mu$ are the components of the Polder permeability tensor. The upper signs are used for the + mode ($e^{jn\phi}$), and the lower signs for the − mode ($e^{-jn\phi}$). The upper and lower solid curves in Fig. 2 show the $x_2$ roots of Eq. (1) for the n = 1 mode of the latched circulator as a function of $\frac{K}{\mu}$. The existence and inequality of the real roots provide theoretical proof that the resonant frequency splits and, as a result, offers the possibility of achieving circulation.

The condition for circulation employing the n = 1 modes is obtained from the following characteristic equation:

$$J_1'(x_2)\, J_1(x_2) + \frac{\pi^2 \kappa^2}{\mu^2} J_1^2(x_1)\, [Y_1(x_1)\, J_1'(x_2) - Y_1'(x_2)\, J_1(x_1)]\, [J_1(x_1)\, Y_1(x_2) - J_1(x_2)\, Y_1(x_1)] = 0 \quad (2)$$

The solid curve in the center of Fig. 2 shows the normalized outside radius $x_2$ of the latched circulator as a function of $\frac{K}{\mu}$.

Finally, the input wave admittance $G_{RW}$ of the latched circulator at the circulation frequency is given by the following expression:

$$G_{RW} = \frac{\pi\, Y_{eff} \left[J_1'(x_2) - \frac{\kappa}{\mu x_2} J_1(x_2)\right] \left[1 - \frac{\pi\kappa}{\mu} J_1(x_1)\, Y_1(x_1)\right] + \frac{\pi\kappa}{\mu} J_1^2(x_1) \left[Y_1'(x_2) - \frac{\kappa}{\mu x_2} Y_1(x_2)\right]}{\sqrt{3}\, \sin\psi \left\{J_1(x_2) - \frac{\pi\kappa}{\mu} J_1(x_1) \left[J_1(x_2)\, Y_1(x_1) - Y_1(x_2)\, J_1(x_1)\right]\right\}} \quad (3)$$

where $Y_{eff}$ has been given by Fay and Comstock[7]. Fig. 3 shows the normalized wave admittance as a function of parameter $\frac{K}{\mu}$. When $x_1$ is equal to $x_2$, the preceding relations reduce to the forms given by Fay and Comstock[8] for the unidirectionally magnetized ferrite disc.

Fig. 4 is a photograph of an experimental latched circulator which operates at a frequency in the vicinity of 7.3 GHz. The principle of operation of this device was verified by means of experiments in which high-remanence metal discs were used to transport flux through the ferrite cylinder and ring. The 20-dB isolation bandwidth for the assembly shown in Fig. 4 was approximately 4 per cent, the center frequency was 7.325 GHz, and the insertion loss was 0.25 dB. This isolation bandwidth was increased to 8.2 per cent by use of a triple-stub tuner in the transmitting arm.

The 20-dB isolation bandwidth for an assembly similar to that shown in Fig. 4, but employing ferrite discs for flux transport and stub tuners for rf impedance matches, was 4.1 per cent, as shown in Fig. 5. The switching time and energy for this circulator were 2 microseconds and 25 microjoules, respectively.

Fig. 6 shows the isolation, actual and normalized radii, and theoretical and actual input conductances as functions of frequency for a C-band latched circulator employing high-remanence metal discs for flux transport. The 20-db isolation bandwidth for this assembly was 4.85 per cent, and the insertion loss was 0.4 dB. The linear dimensions of this circulator were approximately 25 per cent greater than those of the circulator shown in Fig. 4.

Comparison of experiments with theory showed that, at the center frequency, the actual normalized radius and conductance were respectively 30 and 18 per cent greater than the theoretical values obtained from Figs. 2 and 3 and Eq. (3).

Another assembly, which employed all-ferrite components and only quarter-wavelength transormers for rf-impedance matching, had a 20-dB isolation bandwidth from 5.345 to 5.455 GHz (2 per cent) and an insertion loss of 0.4 dB. The switching time and energy for this circulator were respectively 2 microseconds and 9 microjoules. This switching energy was lower than that of the previous circulator because the coercive force of the ferrite and, therefore, the area of the B-H loop were significantly smaller.

Operation of the latched circulator that employed high-remanence metal discs was also demonstrated in a tunnel-diode amplifier. This amplifier had a maximum gain of 18 dB and a 3-dB bandwidth from 7.201 to 7.460 GHz. Switching of the circulator was also demonstrated with this amplifier.


References

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7. Fay and Comstock, op. cit., p. 18.
8. Ibid., Eqs. (6), (14), (16).


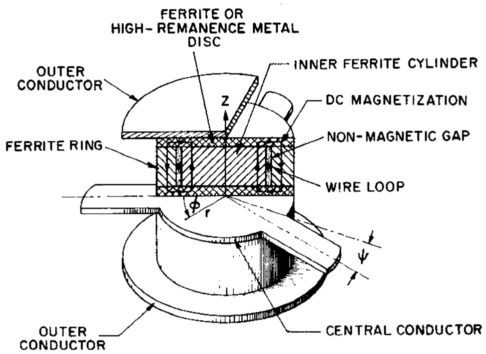


FIG. 1 - Schematic Representation of the Latched Circulator

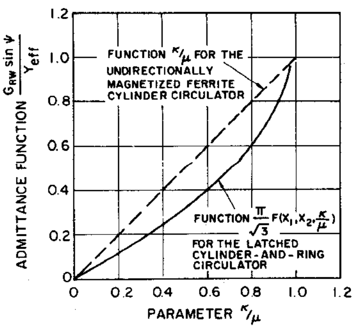


FIG. 3 - Dependance of Admittance Functions for Latched and Unidirectionally magnetized ferrite elements on parameter $\frac{K}{\mu}$

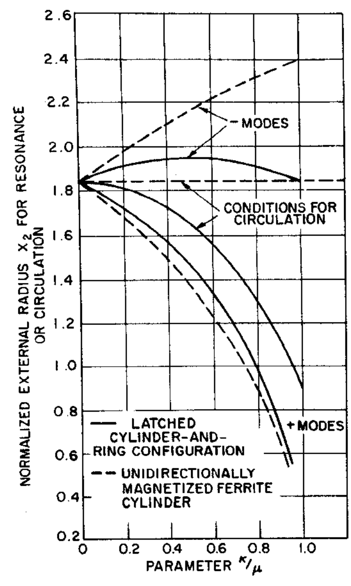


FIG. 2 - Normalized Outside Radii for Resonance and Circulation of Latched and Unidirectionally magnetized ferrite elements for n = 1 Mode as Functions of Parameter $\frac{K}{\mu}$

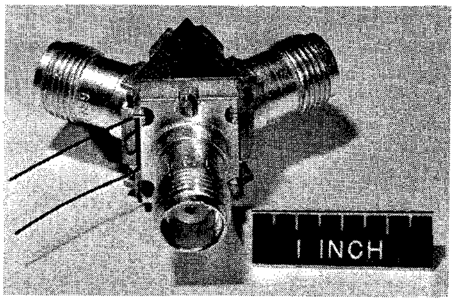


FIG. 4 - Photograph of Latched Switchable Circulator

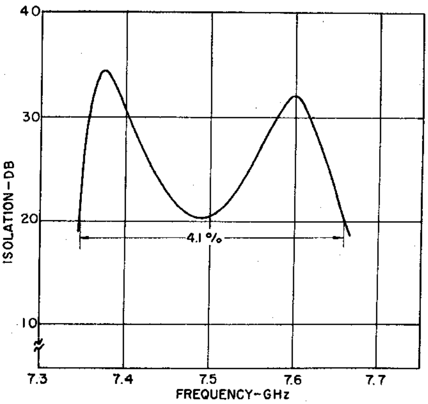


FIG. 5 - Isolation as a Function of Frequency for All-Ferrite Assemblies Employing Stub Tuners

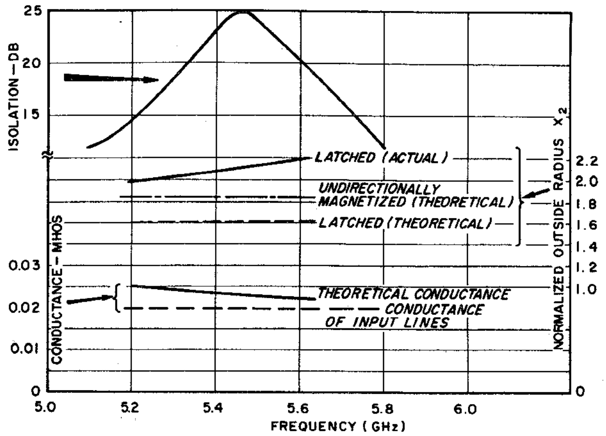


FIG. 6 - Isolation, normalized radii, and input conductance as functions of frequency for a C-band latched circulator employing high-remanence metal discs for flux transport