V-3. NEW DESIGN TECHNIQUES FOR MINIATURE VHF CIRCULATORS

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Since the feasibility of Y junction circulators was first reported in 1959, such circulators have been built to operate in frequency bands from 100 mc to the millimeter wavelength range. All of these circulators appear to operate on essentially the same principle. Using this approach the ferrite disc diameter is proportional to the wavelength. While junction circulators have been useful at microwave frequencies because of their simplicity and small size, such circulators at UHF and VHF frequencies have been expensive and inconveniently large because of the large ferrite volume required. This paper reports the development of a new type of circulator for the VHF and UHF bands. The approach utilizes the lumped element techniques which are natural and convenient for this frequency range and as a result the size of the circulator, and ferrite volume, do not increase with the wavelength. Lumped element circulators have also been developed recently in Japan by Konishi (Reference 1). Figure 1 illustrates the size reduction which has been obtained with the new technique.

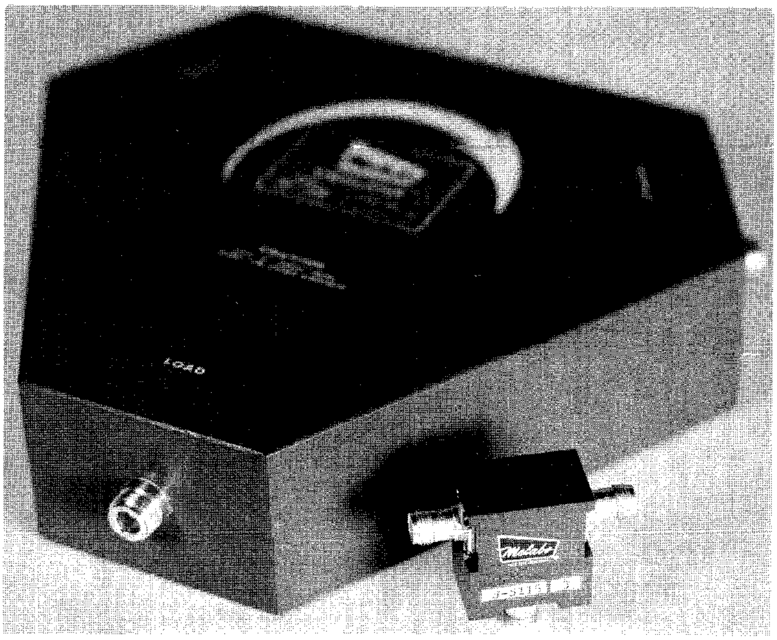


Figure 1. Conventional and Lumped Element 150 mc Circulators

The lumped, nonreciprocal element in the circulator consists of a ferrite disc with three coils wound on it so that the magnetic fields of the coils are oriented at 120 degrees with respect to each other. A d-c field sufficient in strength to bias the ferrite above resonance (i.e., ferromagnetic resonance frequency greater than the operating frequency of the circulator) is applied normal to the plane of the disc. This symmetrical but nonreciprocal element can be used to form a circulator by connecting capacitors either in series or shunt with the load and source impedances as shown in Figure 2. The analysis presented here will consider only the series case. The shunt case can be treated in an analogous manner.

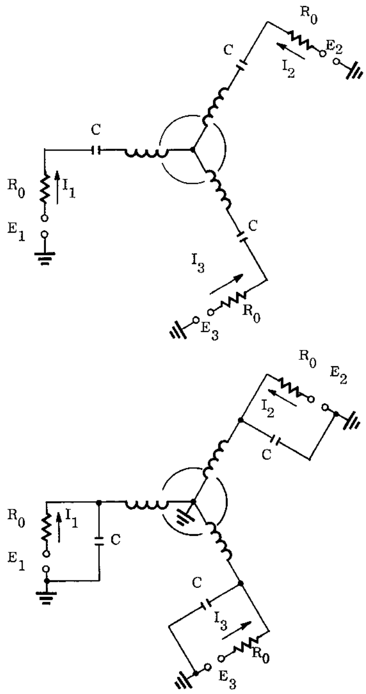


Figure 2. Schematic of Series and Shunt Tuned Circulators

The circulator can be analyzed by expressing E_1, E_2, and E_3 and I_1, I_2, and I_3 in terms of the symmetrical components, e.g.:

$$
\begin{aligned}
E_1 &= E^o + E^+ + E^- & I_1 &= I^o + I^+ + I^- \\
E_2 &= E^o + a^2E^+ + aE^- & I_2 &= I^o + a^2I^+ + aI^- \qquad (1) \\
E_3 &= E^o + aE^+ + a^2E^- & I_3 &= I^o + aI^+ + a^2I^- \\
a &= e^{j2\pi/3}
\end{aligned}
$$

For this case I^o is equal to zero.

To a good approximation the magnetic fields in the ferrite can be idealized by considering them to be circularly polarized for the plus and minus sequence voltages and currents. Then, for the case of the series capacitance:

$$\frac{E\pm}{I\pm} = R_o + j\left(\omega L\pm - \frac{1}{\omega C}\right). \tag{2}$$

L± is proportional to the scalar permeabilities of the ferrite:

$$L\pm = L_o \mu\pm = L_o\left(1 + \frac{\omega_m}{\omega_o \mp \omega}\right) \tag{3}$$

$\omega_m = \gamma 4\pi M_s$

$\omega_o = \gamma H_{int}$

ω = angular signal frequency.

Application of the requirements for an ideal circulator at frequency ω, (i.e.: $E_2 = E_3 = I_3 = 0$) leads to the following conditions for circulation:

$$\frac{\omega}{2}(L^+ - L^-) = \frac{R_o}{\sqrt{3}} \tag{4}$$

$$\frac{\omega}{2}(L^+ + L^-) = \frac{1}{\omega C}. \tag{5}$$

Note that the inductance rather than the ferrite volume as such is the significant parameter. Equivalent performance can be obtained with a small ferrite disc with many turns in the coil around it and with a large disc with only one turn. Equations (4) and (5) do not specify the design uniquely. For example, with a given frequency, impedance level, and $4\pi M_s$ a large value of L_o can be used with the ferrite biased far from resonance ($\omega_o >> \omega$); or at the other extreme, a small value of L_o can be used with the ferrite biased close to resonance (ω_o only slightly greater than ω). This choice is not arbitrary, however, since the proximity to resonance determines the bandwidth and insertion loss of the circulator.

The input impedance and bandwidth of the circulator can be expressed simply if the frequency variation of μ^+ and μ^- is neglected. The input impedance is then that of a series resonant circuit in series with R_o. The bandwidth for 20 db isolation is given by:

$$\frac{\Delta\omega_{20\,db}}{\omega} = 0.2\sqrt{3}\,\frac{\mu^+ - \mu^-}{\mu^+ + \mu^-} = 0.2\sqrt{3}\,\frac{\omega_m \omega}{\omega_o^2 - \omega^2 + \omega_o \omega_m} \tag{6}$$

As a result the bandwidth increases as the bias approaches resonance. A more accurate analysis includes the frequency variation of the permeability, the effect of which is to decrease slightly the theoretical bandwidth, particularly close to resonance.

The insertion loss due to ferrite losses can be estimated by assuming the idealized Lorentzian resonance curve for the ferrite. The result in terms of the 3 db linewidth is:

$$L = 20\log_{10}\left[\frac{4\left(\frac{\omega_o^2}{\omega^2} - 1\right) + \frac{3\gamma\Delta H}{\sqrt{3}\omega}\left(\frac{\omega_o^2}{\omega^2} + 1\right)}{4\left(\frac{\omega_o^2}{\omega^2} - 1\right) + \frac{\gamma\Delta H}{\sqrt{3}\omega}\left(\frac{\omega_o^2}{\omega^2} + 1\right)}\right] \tag{7}$$

As would be expected the loss increases as the linewidth increases; as the ferrite becomes magnetized closer to resonance, and, if $\frac{\omega_0}{\omega}$ is held constant, as ω decreases.

It is seen that for this basic single tuned circulator, wide bandwidth can be obtained only at the expense of increased insertion loss, by biasing close to resonance. An alternative is the use of additional resonant circuits on each port to partially cancel the frequency variation of the single tuned circulator as shown in Figure 3.

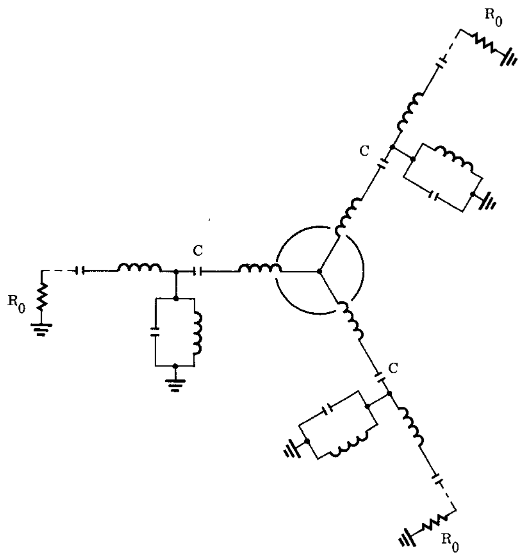


Figure 3. Schematic of a Multiple Tuned Circulator

Lumped element circulators have been operated over the 35 to 1000 mc range. For a given percentage bandwidth the insertion loss increases as the frequency decreases. With a 4 percent 20 db bandwidth the minimum insertion loss varies from about 0.3 db at 400 mc to 0 8 db at 100 mc. Figure 4 is a photograph of a single tuned circulator. Figure 5 compares the performance of a double tuned and single tuned circulator. The minimum loss is degraded slightly by the losses of the additional resonant circuits.

REFERENCE

1. Konishi, Y., "Lumped Element Y Circulator," International Conference on Microwaves, Circuit Theory, and Information Theory, Tokyo, Japan, September, 1964.

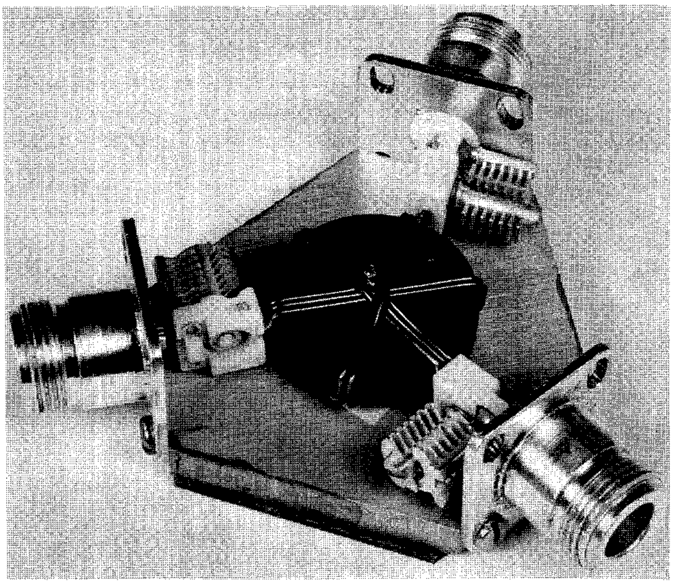
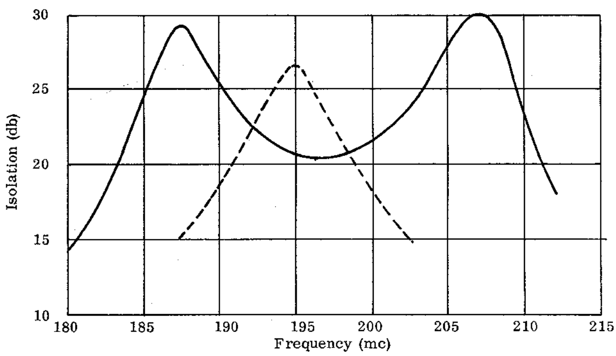


Figure 4. Photograph of a Single Tuned Lumped Element Circulator



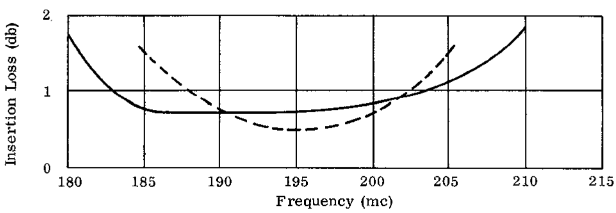


Figure 5. Performance of a Double Tuned and a Single Tuned Circulator

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