CONCLUSION

Group-delay and dissipation loss in stepped-impedance transmission-line filters has been considered. The formulas are novel in that they were derived by transmission-line methods and use only transmission-line parameters. The formulas reduce to known formulas for lumped-constant filters in the case of narrow-band selective filters, but hold more generally for stepped-impedance filters of any bandwidth and any selectivity.

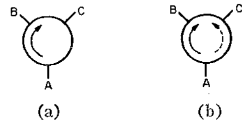
LEO YOUNG
Stanford Research Institute
Menlo Park, Calif.

Reciprocal and Nonreciprocal Switches Utilizing Ferrite Junction Circulators*

The symmetrical ferrite junction circulator has assumed a position of prominence in recent years due to its small physical size and excellent electrical characteristics. The device was described theoretically by Auld,[1] and other investigators have contributed to the design of improved electrical characteristics.[2–4] Due to their low loss, these circulators have found wide use with parametric and tunnel diode amplifiers. Other applications include duplexers, multiplexers and load isolators.

As with all types of circulators, if the sense of the magnetic field is reversed, the direction of circulation reverses, making the design of modulators and switches possible. It is the purpose of this communication to emphasize these properties of junction circulators and discuss possible circuits for both reciprocal and nonreciprocal switching. Some of the experimental characteristics of these devices will also be presented.

The junction circulator is represented schematically as indicated in Fig. 1(a) where the arrow indicates the direction of circulation. The implication is that power entering at Port A leaves at Port B, or power entering at Port B leaves at Port C, etc. A switchable circulator is depicted in Fig. 1(b). The schematic has both a solid and dashed arrow representing the direction of circulation in the two states of the applied magnetic field. In one position, the direction of the circulation is ABC and in the switched position, represented by the dashed arrow, the direction of circulation is ACB. It is obvious that the circuit of Fig. 1(b) represents a single pole-double throw switch; that is, an input at Terminal A can be switched to Terminal B or Terminal C by alternating the direction of applied magnetic field. A photograph of such a switch designed for the S-band region is shown in Fig. 2.



(a) (b)

Fig. 1—(a) Circulator. (b) Switchable circulator.

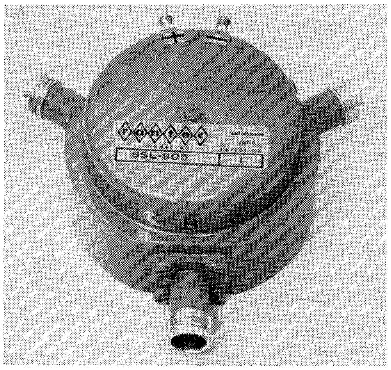


Fig. 2—Switchable circulator for the 2.0-kMc band. The unit performs the function of a nonreciprocal single pole-double throw switch.

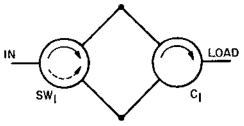


Fig. 3—Reactive, single pole-single throw reciprocal switch.

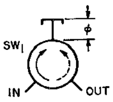


Fig. 4—Reactive balanced modulator or switch.

There are several properties of this type of junction switch that should be pointed out. First, the device is nonreciprocal; second the impedance is not constant during switching; and third, fast switching times are difficult to achieve.

The first property is apparent from a study of Fig. 1(b). When the switch is connected between A and B, B is connected to C instead of A and duplexing of the switched signal cannot be accomplished. Furthermore, the isolation between the two loads at B and C is determined, not only by the circulator, but by how well the loads are matched to the transmission line.

The second item can be understood by considering the nature of the circulator at zero field. In this condition the device is a *reciprocal* 3-port (circulation occurs in both directions with equal amplitude) and cannot be matched bilaterally from port to port. The VSWR can be as high as 2:1 during switching. If this condition is intolerable to the system, it can be overcome by the addition of an isolator at the input of the switch.

The difficulty in achieving fast switching times in these devices is caused by demagnetizing fields and eddy currents. The strong demagnetizing fields in the circulator are due to the disk-shaped ferrite geometries used. These fields oppose the applied field and more switching power is required. The demagnetizing field can be reduced by making the ferrite longer with respect to its diameter.

Eddy currents are present in the coil forms as well as in the ground planes and the center strip of the circulator transmission lines. These currents are difficult to reduce in practice. "Thin wall" techniques have been tried with some success; however, it is felt that 100 μsec seems a practical limit for these devices using reasonable switching power. One μsec switching does not appear practical at this stage of development.

In the discussion to follow, a number of different switching circuits using 3-port junction circulators will be presented. These circuits should cover most switching requirements, both reciprocal and nonreciprocal.

SINGLE POLE-SINGLE THROW (RECIPROCAL)

A single pole-single throw reciprocal switch can be obtained by combining the switchable circulator with a nonswitchable 3-port circulator. The arrangement utilized for this function is shown in Fig. 3. When the switchable circulator is in the state shown by the solid arrow, the input is connected to the load, and the load is similarly connected to the input. In the position indicated by the dashed arrow, power flows from the input around the loop containing C_1 and back out the input without being connected to the load. Similar power flow occurs looking into the load terminal. This circuit, therefore, is reactive in nature and the energy is either transmitted or reflected from the input in the two switched positions. This circuit is the basic building block of some of the switches that follow.

BALANCED SWITCH (RECIPROCAL)

A balanced switch having single pole-single throw characteristics is shown in Fig. 4. In this device, one of the three ports is terminated in an adjustable length short circuit. In one direction of circulation, indicated by the solid arrow, the power at the input travels to the short circuit, is reflected and emerges from the output. In the other direction of circulation, indicated by the dashed arrow, the power at the input feeds directly to the output. Therefore, in *both* switched positions, the input is connected to the output. At zero field the direction of circulations are opposite and equal in magnitude. It is then possible to adjust the phase length (ϕ) of the short circuit so that at the output the two paths will be 180° out of phase and the energy will be reflected back to the input. When this balance is realized, the switch has total reflections at zero field and is transmitting in either direction of the applied field. This device, besides acting as a switch, will provide the function of balanced modulation if its solenoid is driven by a symmetrical periodic waveform. That is, the output will contain an upper and lower sideband spectrum with a suppressed carrier. For broad-band performance, ϕ should have the smallest possible value.

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* Received February 19, 1963.

[1] B. A. Auld, "The synthesis of symmetrical circulators," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-7, pp. 238–246; April, 1959.

[2] L. Davis, U. Milano, and J. Saunders, "A strip line L-band compact circulator," PROC. IRE (*Correspondence*), vol. 48, pp. 115–116; January, 1960.

[3] J. B. Thaxter and G. S. Heller, "Circulators at 70- and 140-kMc," PROC. IRE (*Correspondence*), vol. 48, pp. 110–111; January, 1960.

[4] J. Clark, "Miniaturized, temperature stable, coaxial Y-junction circulators," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES (*Correspondence*), vol. MTT-9 , pp. 267–269; May, 1961.

SINGLE POLE-DOUBLE THROW (RECIPROCAL)

If it is desired to produce reciprocal single pole-double throw action, this can be done efficiently by using one nonreciprocal switchable circulator and two fixed circulators as shown in Fig. 5.

The action of the switch can be seen by following the path of the power flow. Power enters SW_1 and proceeds in the sense of the solid arrow through C_1 to Load 1. Power returned from Load 1 proceeds through C_2 and SW_1 back to the input. When SW_1 is switched so that the dashed arrow applies, power entering at the input proceeds through C_2 to Load 2. Power returned from Load 2 travels to C_1 and then to SW_1 and back to the input. This switch then produces reciprocal power flow. The forward- and reverse-phase in this switch may be different although it could be adjusted by choosing proper line lengths. The insertion loss in the two directions are not equal since, in the forward direction one suffers the loss of two circulators, while in the reverse direction the loss is due to passing through three circulators.

A reciprocal single-pole N-throw switch can be obtained by combining single pole-double throw switches, either in a parallel or series arrangement. A series arrangement is shown in Fig 6.

DOUBLE POLE-DOUBLE THROW (NONRECIPROCAL)

A nonreciprocal double pole-double throw switch can be designed using two switchable junction circulators. This circuit is shown in Fig. 7. When the two switches are electrically ganged together, the switching action can be seen as follows. First, when the solid arrow applies, In_1 is connected to Out_1 and In_2 is connected to Out_2 by the energy passing directly through SW_1 and SW_2, respectively. When the circulators are switched and the dashed arrows apply, In_1 is connected to Out_2 by energy passing through both SW_1 and SW_2. Similarly. In_2 is connected to Out_1. The switch is nonreciprocal since the following sequences apply.

Solid Arrow	Dashed Arrow
$\mathrm{In}_1 \rightarrow \mathrm{Out}_1$	$\mathrm{In}_1 \rightarrow \mathrm{Out}_2$
$\mathrm{In}_2 \rightarrow \mathrm{Out}_2$	$\mathrm{In}_2 \rightarrow \mathrm{Out}_1$
$\mathrm{Out}_1 \rightarrow \mathrm{In}_2$	$\mathrm{Out}_1 \rightarrow \mathrm{In}_1$
$\mathrm{Out}_2 \rightarrow \mathrm{In}_1$	$\mathrm{Out}_2 \rightarrow \mathrm{In}_2$

DOUBLE POLE-DOUBLE THROW (RECIPROCAL)

The switch of Fig. 8 can be made reciprocal by the addition of two circulators as shown schematically in Fig. 8.

The reader can verify that the following switching sequences take place.

Solid Arrow	Dashed Arrow
$\mathrm{In}_1 \rightarrow \mathrm{Out}_1$	$\mathrm{In}_1 \rightarrow \mathrm{Out}_2$
$\mathrm{In}_2 \rightarrow \mathrm{Out}_2$	$\mathrm{In}_2 \rightarrow \mathrm{Out}_1$
$\mathrm{Out}_1 \rightarrow \mathrm{In}_1$	$\mathrm{Out}_1 \rightarrow \mathrm{In}_2$
$\mathrm{Out}_2 \rightarrow \mathrm{In}_2$	$\mathrm{Out}_2 \rightarrow \mathrm{In}_1$

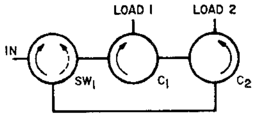

Fig. 5—Reciprocal single pole-double throw switch.

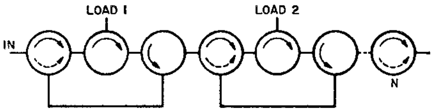

Fig. 6—Series arrangement of single pole-double throw reciprocal switches to make single pole-N throw switch.

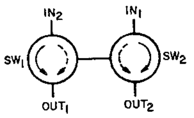

Fig. 7—Double pole-double throw nonreciprocal switch.

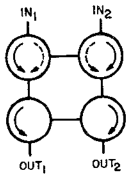

Fig. 8—Double pole-double throw reciprocal switch.

EXPERIMENTAL CHARACTERISTICS

The three-port circulator shown in Fig. 2, having broad-band tuning, was investigated experimentally to observe its switching characteristics. The instantaneous bandwidth with a fixed field is shown in Fig. 9. The insertion loss vs coil current for several frequencies is shown in Fig. 10. An important characteristic should be noted from Fig. 10. It is difficult to overdrive this type of switch. The isolation and insertion loss show little change when one applies additional current to the unit. This is obviously not true in Faraday rotation switches, or switches utilizing phase shift principles. The fact that the switches are not current sensitive is an advantage to the systems engineer who need not worry about the design of a precision driver. Hysteresis measurements have shown this switch to have a maximum separation of 2 db between increasing and decreasing currents after driving the switch into saturation. Some of the hysteresis is due to the iron coil-forms used.

The coil current required is somewhat arbitrary and can be controlled by the number of turns and wire size. For fast switching requirements, inductance must also be controlled and some freedom of choice is lost. The holding power can be made extremely small by careful design. For example, a switch designed for space applications drew a current of 10 ma at 1 3/4 volts for proper operations.

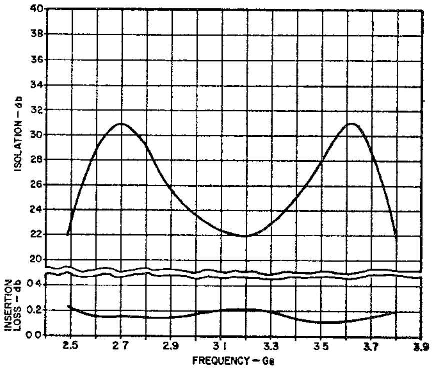

Fig. 9—Instantaneous isolation and insertion loss bandwidth of 3-port switchable junction circulator with fixed field.

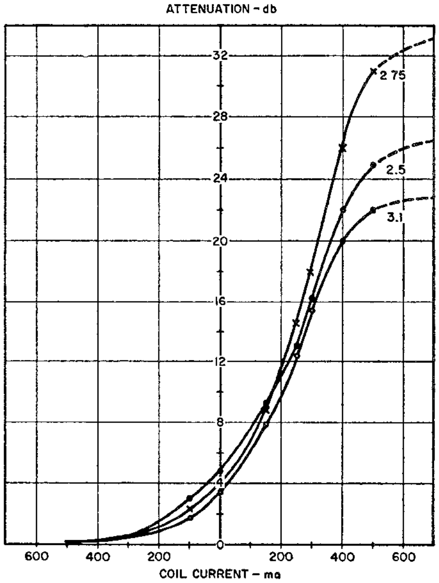

Fig. 10—Attenuation vs coil current for various frequencies for a switchable junction circulator. Only one-half of the frequency band is shown.

Several arrangements for combining nonreciprocal, three-port switches with three-port circulators to produce reciprocal switches have been described. Single pole-single throw, single pole-double throw, double pole-double throw as well as balanced switches can be designed. These switches do not require exact values of switching current to obtain their best performance, and should find system use due to their small physical size. Some problems may be encountered with these devices due to their nonconstant input impedance during switching, as well as the difficulty in obtaining very rapid switching times.

ALVIN CLAVIN
RANTEC Corp.
Calabasas, Calif.

Mixed Two-Port Parameters for Characterizing Varactor Mounts in Waveguides*

In the design of harmonic generators using varactors in waveguide mounts, one of the most important problems is to determine

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