remanent states.[5] However, in many applications, where a few microseconds switching times can be tolerated, this effect will not be harmful.

Experimental Results

Two experimental C-band models have been fabricated. One of these employs a single toroid of ferrite material ($4\pi M_s=1700$ gauss) while the other utilizes a toroid made from a temperature compensated garnet material ($4\pi M_s=1200$ gauss). In each design, the length of the toroid has been adjusted to give a maximum of 360° differential phase shift when latched between remanent states. As can be seen from Fig. 3, an incremental phase shifter can be obtained by providing various amplitude positive pulses along with accompanying negative reset pulses. For example, eight controlled amplitude positive pulses are required to correspond to a present three-bit design while sixteen pulses are needed for a four-bit design.

Experimental data for the two model phase shifters compare quite favorably with multitoroid designs. The new models exhibit compactness (<4 inch length for ferrite model and <6 inch length for garnet model), reduced insertion loss (<0.5 dB for ferrite model) and exhibit improved temperature characteristics when switched to intermediate states. A maximum switching time of approximately 4 micoseconds is required for the reset-controlled amplitude pulse sequence. Curves and other data describing the switching characteristics of the new phase shifters are given in Whicker and Jones.[6]

Acknowledgment

The authors wish to thank Dr. G. S. Blevins and J. A. Kempic for many helpful discussions on latching ferrite devices, and J. A. Osborn for advice concerning partial demagnetization effects.

L. R. Whicker
R. R. Jones
Applied Physics Lab.
Surface Division
Westinghouse Def. and Space C.
Baltimore, Md.

[5] F. Sterzer, "Millimicrosecond microwave ferrite-modulator," *Proc. IRE*, vol. 47, pp. 98–100, January 1959.

[6] L. R. Whicker and R. R. Jones, "A digital current controlled latching ferrite phase shifter," *1965 IEEE Internat'l. Conv. Rec.*, pt. 5, pp. 217–223.

General Three-Resonator Filters in Waveguide

General three-resonator filters are capable of providing both band-pass and band-reject behavior. This type of filter network

Manuscript received September 7, 1965. This work was performed for the Rome Air Development Center under Contract AF30(6021-3648).

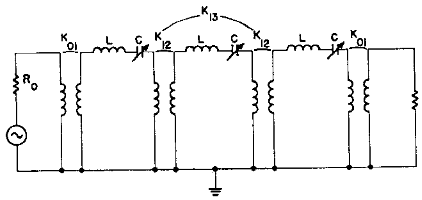

Fig. 1. Lumped-circuit, low-frequency general three-resonator filter.

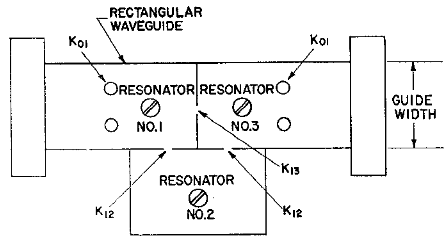

Fig. 2. Simplified layout, general three-resonator waveguide filter.

has been briefly considered as a generalized triple-tuned circuit [1]. The potential advantages of general three- and four-resonator filters have been more recently discussed by Johnson, who considers *dissipationless* filters using inductive couplings [2]. Johnson has presented experimental data on a lumped-circuit element general filter at 20 Mc/s, and has suggested some techniques for microwave implementation of general filters. In this correspondence, the performance capabilities of *dissipative* general three-resonator filters in waveguide will be discussed.

The schematic of a lumped-circuit, low-frequency general three-resonator filter is filter is shown in Fig. 1. This is one possible prototype of the general three-resonator filter in rectangular waveguide using inductive susceptances as coupling elements between adjacent resonators. A simplified layout of the general three-resonator filter, as realized in rectangular waveguide, is shown in Fig. 2. A picture of the filter model can be seen in Fig. 3.

Double inductive posts are used as input/output couplings, K_{01} (Fig. 1). Interstage couplings K_{12} use side-wall circular apertures similar to those employed in sidewall directional couplers. Bridging coupling K_{13} uses an inductive circular iris in a thin metallic plate separating resonators one and three. Capacitive tuning screws are used in each resonator.

The design of narrow-band general filters in waveguide can be implemented using the procedures of Cohn [3] and/or Dishal [4], [5] with modifications to accommodate the bridging coupling K_{13}. For interstage couplings, it has been shown that an interchangeability exists between normalized susceptances and coefficients of coupling [6]. Two direct-coupled waveguide filter models were subsequently developed in RG-52/U waveguide. The first model was a conventional band-pass filter designed for a Butterworth response shape at a center frequency of 8900 Mc/s. Input/output couplings K_{01} were double inductive posts of 0.062-inch diameter with 0.412-inch spacing between post centers, resulting in a normalized susceptance, $B_{01}=5.0$. Interstage couplings K_{12} were triple inductive posts of 0.093-inch diameter, with 0.550-inch spacing between post centers of the two offset posts, resulting in a normalized susceptance, $B_{12}=37.3$. The insertion loss vs. frequency response of this filter is shown in Fig. 4. The second model was the general band-pass filter previously described. K_{12} was realized using sidewall coupling apertures of 0.323-inch diameter, resulting in a normalized susceptance, B_{12}

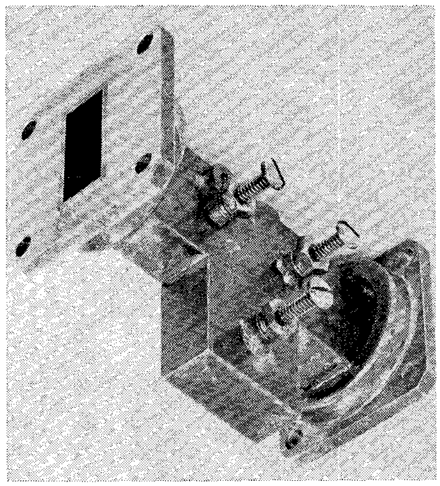

Fig. 3.

$=37.3$. The bridging coupling K_{13} used an 0.156-inch diameter iris of 0.031-inch thickness, resulting in a normalized susceptance, $B_{13}=90$. This iris was soldered to the top and bottom walls of the waveguide, with 0.031-inch air gaps between the metallic edges and the waveguide side walls. The insertion loss vs. frequency responses of the general filter is shown in Fig. 5. The response curves of Figs. 4 and 5 are plotted together in Fig. 6. It can be seen that the general filter provides peak rejection and enhanced selectivity on the high-frequency skirt, at a price of degraded selectivity on the low-frequency skirt, and a modest increase in pass-band dissipation loss.

The theoretical performance of the general three-resonator filter can be determined as follows.

Peak rejection should occur at a normalized frequency X:

$$X = +K_{12}\left(\frac{K_{12}}{K_{13}}\right) = K_{12}\left(\frac{B_{13}}{B_{12}}\right); \quad (1)$$

K_{12} and K_{13} are normalized coefficients of coupling. Letting $K_{12}=0.707$, $B_{13}=90$, and $B_{12}=37.3$

Letting $K_{12}=0.707$, $B_{13}=90$, and $B_{12}=37.3$

$$X=+1.72$$

where

$$X \cong 2\left(\frac{f-f_0}{\Delta f_{3\,\mathrm{dB}}}\right)$$

f_0 = filter center frequency
$f_{3\,\mathrm{dB}}$ = filter 3 dB bandwidth

Letting f = frequency of peak rejection:

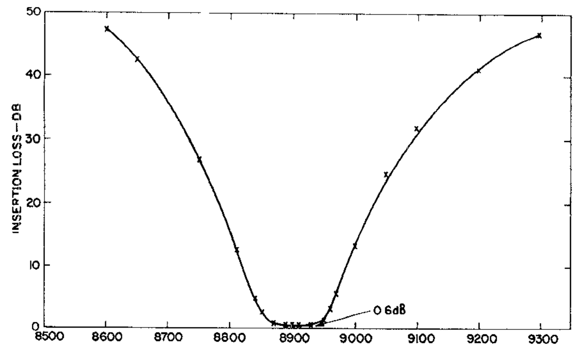

Fig. 4. Insertion loss vs. frequency response, conventional waveguide band-pass filter.

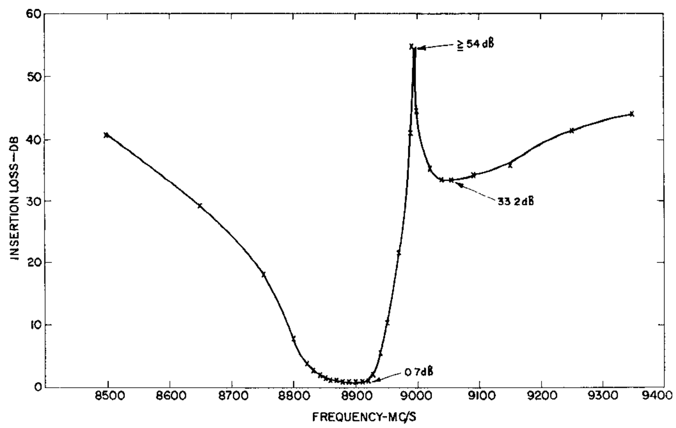

Fig. 5. Insertion loss vs. frequency response, general waveguide band-pass filter.

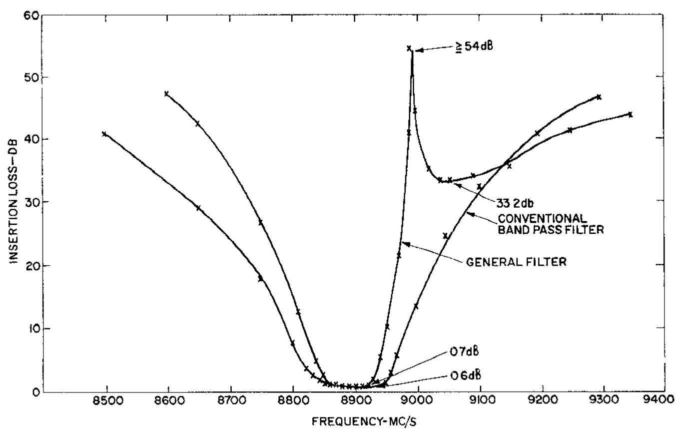

Fig. 6. Comparison of insertion loss vs. frequency responses.

$$f = f_0 + \left(\frac{\Delta f_{3\,\mathrm{dB}}}{2}\right)$$

$$X = 8900 + 1.72\left(\frac{100}{2}\right) = 8986 \text{ Mc/s};$$

the measured frequency of peak rejection was 8995 Mc/s.

The theoretical insertion loss at the frequency of peak rejection is approximately equal to the sum of two components:

$$\text{I.L.} = P + R, \quad (2)$$

$$P = 10 \log (1 + X^6), \quad (3)$$

$$R = 20 \log \left[\frac{1}{2K_{13}d_2}\right] \quad (4)$$

where

$$d_2 = \frac{Q_T}{Q_{UL}} = \text{normalized dissipation factor o second resonator.}$$

Now

$$Q_T = \frac{f_0}{\Delta f_{3\,\mathrm{dB}}} = \frac{8900}{100} = 89.$$

Letting

$$Q_{UL} = \text{unloaded } Q \text{ of second resonator} = 4000,$$

$$d_2 = \frac{89}{4000} = 0.0222.$$

For $X = 1.72$, using (3), $P = 14.2$ dB. Letting $K_{13} = 0.291$, $d_2 = 0.0222$; using (4), $R = 37.8$ dB. Then $P + R = 52$ dB, which can be compared to a measured peak rejection of $\geqq 54$ dB.

The pass-band insertion loss of the general three-resonator waveguide filter can also be determined.

$$\text{I.L.} \cong 10 \log [A_0^2 + A^2], \quad (5)$$

where

$$A_0 = d_1^2 d_2 + K_{13}^2 d_2 + 2K_{12}^2 d_1, \quad (6)$$

$$A = 2K_{12}^2 K_{13}. \quad (7)$$

Letting $d_1 = 1$, $d_2 = 0.0222$, $K_{12} = 0.707$, $K_{13} = 0.291$, $A_0^2 = 1.05$, and $A^2 = 0.085$. Then the pass-band insertion loss using (5) will be 0.6 dB, as compared to a measured pass-band insertion loss of 0.7 dB.

Reasonably good correlation between theory and experiment has been attained. The general three-resonator waveguide filter described herein is applicable to situations requiring asymmetrical selectivity. Possible areas of practical usage include diplexer filters and sideband selection filters.

RICHARD M. KURZROK
RCA Commun. Systems Lab.
New York, N. Y.

REFERENCES

[1] N. W. Mather, "An analysis of triple-tunnel coupled circuits," *Proc. IRE*, vol. 38, pp. 813–822, July 1950.
[2] E. C. Johnson, "New developments in designing bandpass filters," *Electronic Industries*, pp. 87–90, 92, 94, January 1964.
[3] S. B. Cohn, "Direct-coupled resonator filters," *Proc. IRE*, vol. 45, pp. 187–196, February 1957.
[4] M. Dishal, "Design of dissipative band-pass filters producing desired exact amplitude-frequency characteristics," *Proc. IRE*, vol. 37, pp. 1050–1069, September 1949.
[5] M. Dishal, "Alignment and adjustment of synchronously-tuned multiple-resonant-circuit filters," *Proc. IRE*, vol. 39, pp. 1448–1455, November 1951.
[6] R. M. Kurzrok, "Couplings in direct-coupled waveguide band-pass filters," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 389–390, September 1962.

Peak-Pulse Power Calibrations Initiated

The Radio Standards Laboratory at Boulder, Colorado, has inaugurated a new service for the calibration of coaxial RF peak-pulse power meters. This service is available for a frequency band of 950 to 1200 MHz and a peak-power range of 1 mW to 3 kW. Calibrations are performed at pulse widths of 2 to 10 μs and repetition rates of 100 to 1600 pps, with a maximum duty cycle of 0.0033 due to generator limitations.

The calibration system shown in Fig. 1 makes use of a sampling-comparison method. This method[1] employs a specially-constructed diode switch to extract a sample of

Manuscript received October 27, 1965.

[1] P. A. Hudson, W. L. Ecklund, and R. A. Ondrejka, "Measurement of RF peak-pulse power by a sampling-comparison method," *IRE Trans. on Instrumentation*, vol. I-II, pp. 280-284, December, 1962.