30-GHz-Band Periodic Branching Filter Using a Traveling-Wave Resonator for Satellite Applications

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Abstract—**A periodic branching filter consisting of three directional couplers, a traveling-wave resonator, and connecting waveguides is used as a band diplexer with a broad 3-dB bandwidth and sharp selectivity for a satellite communication system application. This paper describes a theoretical analysis, a design method, and experimental results for this periodic branching filter. The fabricated periodic branching filter for separating the 30-GHz frequency band 27.0–29.2 GHz into two subbands of equal 3-dB bandwidth of about 900 MHz has sharp frequency selectivity. Measured branching losses and relative delay time are 0.35–0.5 dB and 0.4 ns, respectively, within each frequency subband ($f_{1,2} \pm 300$ MHz). The 96-g diplexer is made of thin-walled aluminum. Its size is 15 × 9 × 4 cm.**

I. Introduction

The PERIODIC filter, whose amplitude transmission characteristics versus frequency varies periodically, is well known. Several papers about periodic filters have been reported [1]–[7]. Periodic channeling filters composed of two 3-dB directional couplers and connecting waveguides have been reported [1]–[4]. However, the disadvantage of these filters is the frequency characteristics, given by sine or cosine functions. In [5], a periodic filter is composed of a magic tee with two short-circuited waveguides and its frequency characteristics are improved by using a stub section in waveguides. On the other hand, in [6] and [7], frequency characteristics are improved by using a dielectric cavity within the waveguides. For another frequency improving method, a periodic filter using a traveling-wave resonator is proposed by K. Miyauchi [8]. This filter is composed of a traveling-wave resonator, three directional couplers, and connecting waveguides.

Features of this periodic filter are as follows.

1) One can easily design not only a narrow 3-dB band but also a wide 3-dB band filter.

2) If the amplitude coupling coefficient k is chosen for critical coupling ($k = 2\sqrt{2}/3$), its frequency transmission characteristics are nearly equal to a 6- or 7-cavity maximally flat type filter.

3) If the resonance point of the resonator is placed at the edge of each channel frequency band, its filter has low-loss characteristics.

4) Composition is simple, thus manufacture of this filter and adjustment of its characteristics are easy.

5) When the branching filter systems are constructed by this filter, at first each channel is branched alternately into two different ports, filters with sharp frequency selectivity are not required.

This paper describes the theoretical analysis, design method, and experimental results of this periodic filter [9]. It was proposed to use this periodic filter as a 30-GHz band diplexer for a communication satellite subsystem.

Manuscript received July 6, 1976; revised February 23, 1977.

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II. Principles of a Periodic Filter

A periodic filter can separate input channel frequencies $f_1 + f_2 + f_3 + f_4 + \cdots$ into $f_1 + f_3 + f_5 + \cdots$ and $f_2 + f_4 + f_6 + \cdots$, alternately. Diagrams of the periodic filter with a traveling-wave resonator are shown in Fig. 1. In Fig. 1(a), a through-type traveling-wave resonator is used, and in Fig. 1(b), a coupling-type resonator is used. As these two types of filters are similarly dealt with, the through-type filter is mainly described here. This filter is composed of a traveling-wave resonator, three directional couplers, and connecting waveguides. Two of these directional couplers are 3-dB hybrids.

The transmission equation between ports ① and ② is given by

$$\frac{a_2}{a_1} = -A_2 e^{-j\Phi_2} \tag{1}$$

where its amplitude A_2 and phase Φ_2 are given by

$$A_2 = \frac{1}{\sqrt{2}}\{1 - \cos(\phi - \beta\Delta l)\}^{1/2} \tag{2}$$

$$\Phi_2 = \tan^{-1} \cot \frac{\phi + \beta(l_a + l_b)}{2}. \tag{3}$$

In the same way, transmission equations between ports ① and ③ are given by

$$\frac{a_3}{a_1} = -A_3 e^{-j\Phi_3} \tag{4}$$

$$A_3 = \frac{1}{\sqrt{2}}\{1 + \cos(\phi - \beta\Delta l)\}^{1/2} \tag{5}$$

$$\Phi_3 = \tan^{-1} \cot \frac{\phi + \beta(l_a + l_b)}{2}. \tag{6}$$

Here, it is assumed that three directional couplers are ideal, and waveguides are lossless. In the above equations, l_a and l_b are the lengths of connecting waveguides, β is its phase constant, and $\Delta l = l_b - l_a$. Phase lag ϕ of the traveling-wave resonator is given by

$$\phi = \tan^{-1} \frac{(p^2 - 1)\sin\theta}{2p - (p^2 + 1)\cos\theta} \tag{7}$$

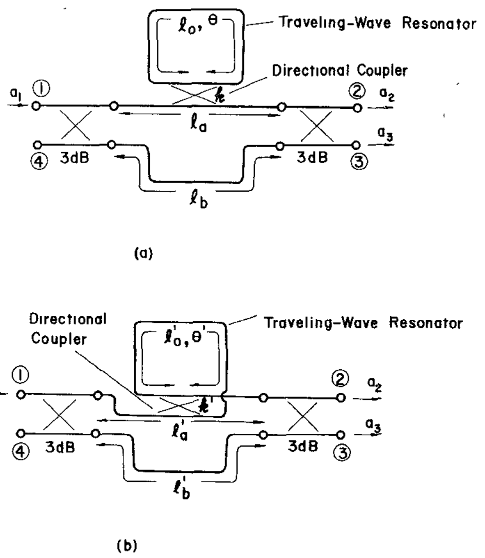

Fig. 1. Equivalent circuits of periodic branching filter with a traveling-wave resonator. (a) Through type. (b) Coupling type.

where $p=\sqrt{1-k^2}$ and k is the amplitude coupling coefficient of the directional coupler. $\theta=\beta l_o$ is the electrical length of the resonator and l_0 is its one-round length.

The amplitude and phase characteristics of this filter can be varied by changing the amplitude coupling coefficient k. If $k=0$ or 1, the amplitude characteristics are given by the function of sine or cosine. Among these various characteristics, this filter shows a critical property, wherein amplitude characteristics are improved or flattened near each center frequency, and there is no leakage to another port. This critical condition is obtained from the two following equations.

1) At antiresonance points of the resonator ($\theta=(2n+1)\pi, n=0,1,2,3,\cdots$), the following relation must be satisfied

$$\Delta l \frac{d\beta}{d\omega}=\frac{d\phi}{d\omega}. \tag{8}$$

2) When the value of θ increases at every antiresonance point, the value of $\phi-\beta\Delta l$ must be increased by about π. Then, we obtain the next relation

$$\beta\Delta l=\beta l_0/2 \pm \pi/2. \tag{9}$$

From (8) and (9), critical amplitude coupling coefficient k is given as follows:

$$k=2\sqrt{2}/3.$$

In Fig. 2(a) and (b), phase and amplitude characteristics of this filter are shown. The horizontal axis indicates the electrical length of the resonator (coincides with the frequency) and the vertical axis indicates the phase or amplitude. In Fig. 2(a), the broken line indicates phase characteristics of $\beta\Delta l$, while the solid line and dash–dot line indicate the phase variation of the resonator at $k=2\sqrt{2}/3$ (critical coupling) and at $k=1$, respectively. From Fig. 2, the two conditions above mean that the inclination of the resonator phase ϕ and $\beta\Delta l$ coincides, and the value of $\phi-\beta\Delta l$ is periodically increased by π at the antiresonance points, as the value of θ increases. In Fig. 2(b), amplitude characteristics are shown.

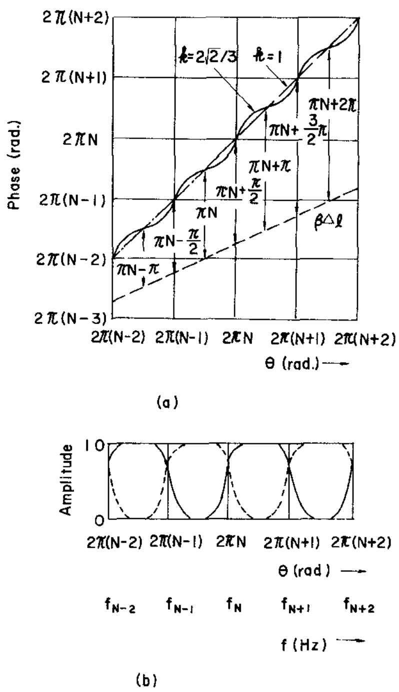

Fig. 2. Phase and amplitude characteristics of periodic branching filter. (a) Phase. (b) Amplitude.

From the same consideration, the critical coupling coefficient of a coupling-type filter is given by $k'=\frac{1}{3}$. The value of k' coincides with the critical value of p ($p=\sqrt{1-k^2}$: $k=2\sqrt{2}/3$). This means that the frequency characteristics of the periodic filter with a traveling-wave resonator, as shown in Fig. 1(a) and (b), are equal in the case of critical coupling conditions. From the above results, a coupling-type periodic filter is determined to be useful in the following case. If the frequency bands between adjacent center frequencies are narrow, the resonator length becomes long and desired coupling can be obtained easily. However, if frequency separations are wide, the resonator becomes short and desired coupling cannot be obtained easily. That is, when the desired coupling cannot be obtained for its channel frequency arrangement or physical dimensions, a coupling-type traveling-wave resonator can be adopted.

Delay characteristics of the filter shown in Fig. 1(a) are given by

$$\tau=\frac{d\Phi_2}{d\omega}=\frac{d\Phi_3}{d\omega}=\frac{1}{2}\left\{\frac{d\phi}{d\omega}+(l_a+l_b)\frac{d\beta}{d\omega}\right\}$$

$$\frac{d\phi}{d\omega}=\frac{(p^2-1)\{2p\cos\theta-(1+p^2)\}}{\{2p-(1+p^2)\cos\theta\}^2+(1-p^2)\sin^2\theta}\cdot\frac{d\theta}{d\omega}$$

$$\frac{d\beta}{d\omega}=\frac{\lambda g}{\lambda}\cdot\frac{1}{c} \tag{10}$$

where λ, λ_g, and c are free space wavelength, waveguide wavelength, and light velocity, respectively.

In Fig. 3(a) and (b), the calculated amplitude transmission characteristics are shown when coupling coefficient k is varied. In Fig. 4(a) and (b), the calculated $d\phi/d\theta$ (normalized

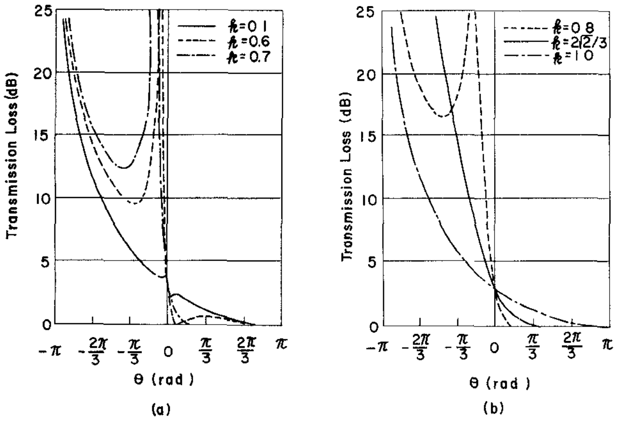

Fig. 3. Calculated amplitude characteristics of periodic branching filter.

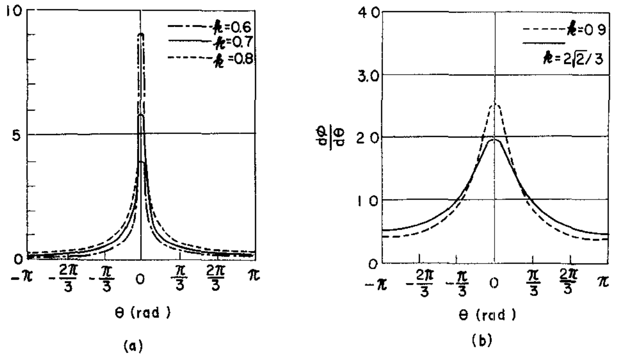

Fig. 4. Calculated delay characteristics of resonator.

delay) of the resonator section are shown. From this figure, if $k = 1$, the amplitude characteristics are given by the function of sine or cosine. If k becomes less than one, the frequency characteristics approach critical conditions. If the value of k becomes smaller than $2\sqrt{2}/3$, amplitude ripples near each center frequency appear and leakages increase in another branching port.

In the case of critical coupling, transmission characteristics are compared with usual maximally flat type filters. The calculated results are shown in Fig. 5(a) and (b). The parameters are given next; branching center frequency: 29.25 GHz; 3 dB bandwidth: 1 GHz; number of wavelength along resonator N: 19; waveguide size: $a \times b = 8.636 \times 4.318$ mm^2. Transmission characteristics are found to be nearly equal to a 6- or 7-cavity maximally flat type filter.

III. Design of Periodic Filter

At first, l_0 and N of the resonator are determined. When the frequency spacing between adjacent channels is B, N is given by

$$N \doteqdot \frac{f_0}{B}\left(\frac{\lambda_0}{\lambda_{g0}}\right)^2$$

where f_0, λ_0, and λ_{g0} indicate resonance frequency, free space wavelength, and waveguide wavelength at f_0, respectively. Resonator length l_0 is given by

$$l_0 = N\lambda_{g0}.$$

Next, coupling coefficient k is determined. In a practical case, for example, when waveguides are used, coupling

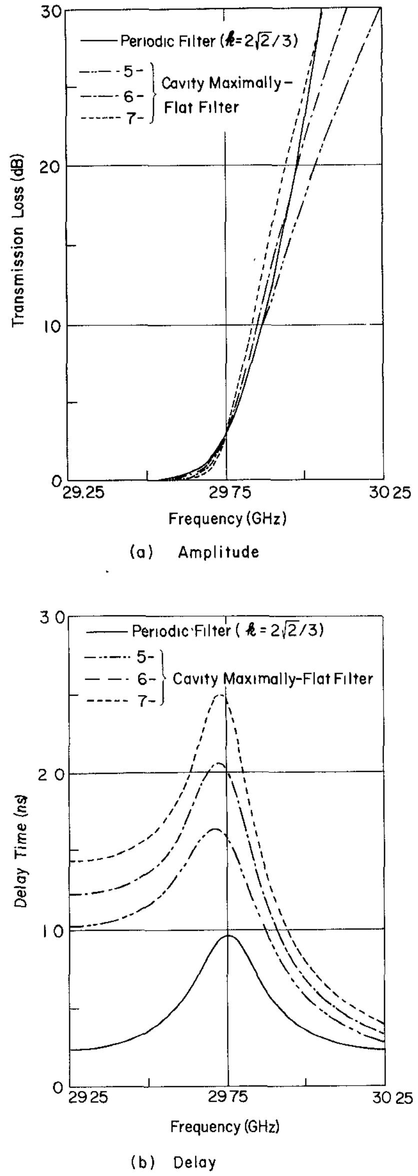

Fig. 5. Comparison between periodic and maximally flat type filter (center frequency: 29.25 GHz, 3-dB bandwidth: 1 GHz, $l_o = 235.76$ mm, $N = 19$, WG: $a \times b = 8.636 \times 4.318$ mm^2). (a) Amplitude. (b) Delay.

characteristics cannot be avoided, no matter what coupling type is adopted. Thus the upper limits of k are determined by amplitude selectivity characteristics of the band edge and the lower limits are determined by leakage to another branching port. Relations between amplitude coupling coefficient k and leakage are shown in Fig. 6. When leakage must be smaller than -20 dB, k must be greater than 0.85. In Fig. 7, relations between frequency (θ/θ_{-3}, $\theta = \beta l_0$, θ_{-3}: θ of 3-dB point) and k are shown as the parameter of band edge amplitude characteristics.

IV. Experimental Results

In the 30-GHz band of the communication satellite subsystem, a wide-band receiver is used, and several communication channel frequencies are converted to IF by one receiver. Therefore, the 3-dB frequency band of this diplexer has to be about 800–900 MHz. Since precise system design of

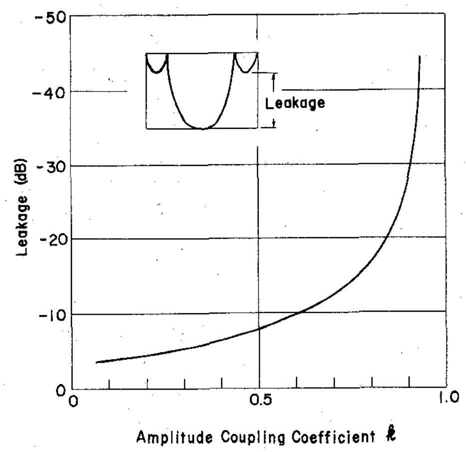

Fig. 6. Leakage as a function of amplitude coupling coefficient k.

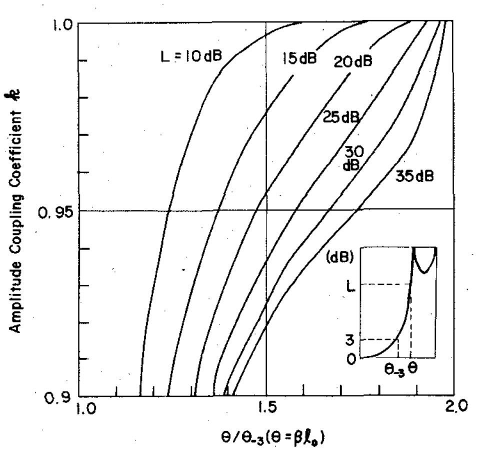

Fig. 7. Relations between amplitude coupling coefficient and amplitude transmission characteristics.

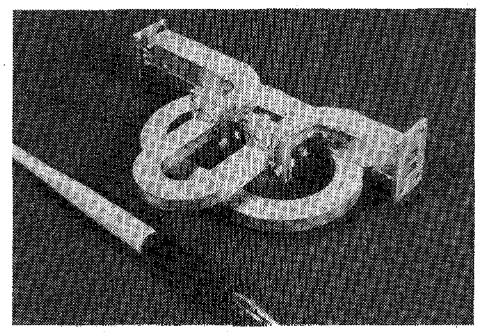

Fig. 8. Fabricated periodic branching filter.

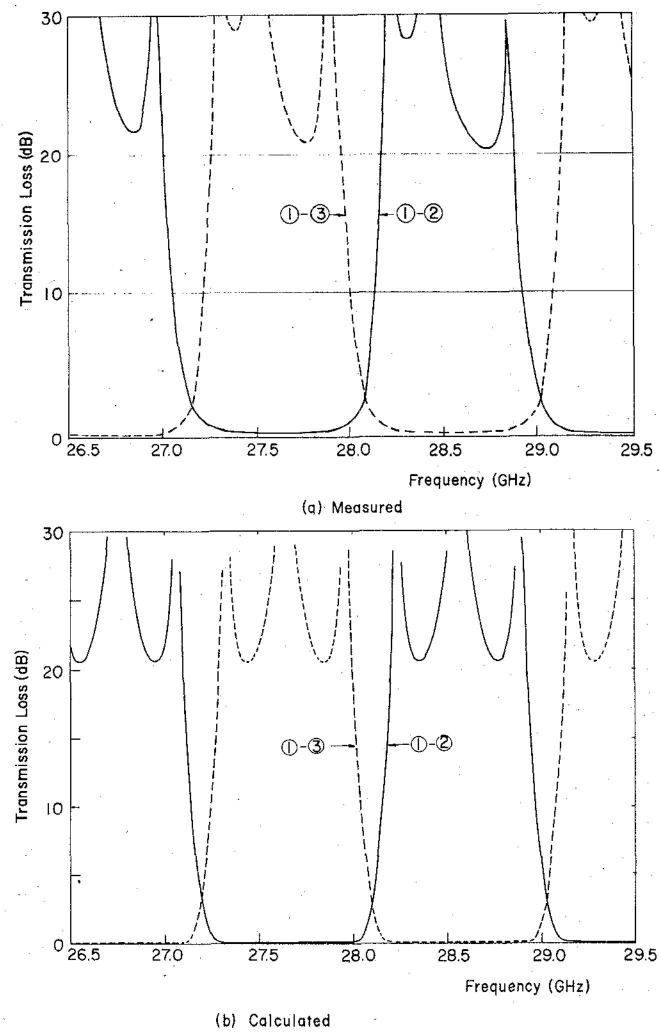

Fig. 9. Amplitude transmission characteristics of the periodic branching filter ($k = 0.85$). (a) Measured. (b) Calculated.

the satellite communication has not been determined, it is assumed that the 30-GHz band (27.0–29.2 GHz) should be divided into two subbands. In this case, each subband contains three or four communication channels. Each communication channel is branched into two groups with minimum loss. Thus frequency selectivity characteristics of the diplexers must be sharper, and leakages to another port must be reduced to the smallest value possible. For this reason, amplitude coupling coefficient k is selected at about 0.85. Other designed parameters of this periodic diplexer are as follows:

resonance frequency of traveling-wave resonator: $f_o = 28.1$ GHz;
3-dB bandwidth: $B \fallingdotseq 900$ MHz;
wavelength number of resonator: $N = 19$;
coupling type of three directional coupler: 7 branch guide.

A fabricated periodic diplexer for communication satellite is shown in Fig. 8. This filter is made from aluminum for weight reduction. Its weight is about 96 g and its dimensions are about 15 × 9 × 4 cm.

Measured and calculated amplitude characteristics of this filter are shown in Fig. 9(a) and (b), respectively. To obtain expected characteristics, it is necessary to adjust the length of connecting waveguides. In this case, waveguide length l_b is varied by inserting waveguide spacers. Amplitude coupling coefficient k of this filter is selected to be about 0.85. However, from Fig. 9(a), the value of k is slightly larger than 0.85. Insertion losses are measured in each subfrequency band. Measured losses in $f_{1,2} \pm 300$-MHz frequency band (f_1, f_2: center frequency of each branching frequency band) are about 0.35–0.5 dB. This diplexer is not plated by any other metal. Measured losses of an experimental model

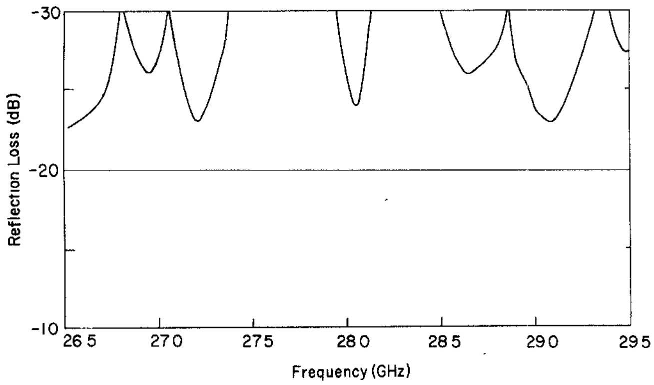

Fig. 10. Reflection characteristics of the fabricated filter.

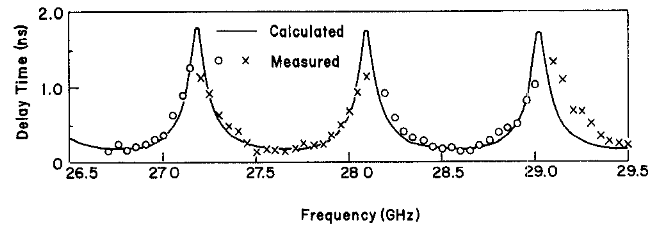

Fig. 11. Delay characteristics of the periodic branching filter.

diplexer plated with silver, but with the same specifications, are 0.27–0.36 dB. If the electrical conductivities of aluminum and silver are estimated, measured data of the fabricated diplexer are considered to be appropriate.

Fig. 10 shows reflection characteristics. The measured maximum reflection level is -23 dB (input VSWR: less than 1.15). Maximum reflection points are mostly situated near resonance frequency because directivity characteristics of the directional coupler connected to the resonator affect this reflection. But, as the resonance frequencies exist near the 3-dB cross point, this reflection does not affect the properties of this diplexer.

Measured and calculated delay characteristics are given in Fig. 11. An amplitude modulation method is taken for this measurement. Measured and calculated relative delay time are 0.4 ns and 0.3 ns, respectively, in the $f_{1,2} \pm 300$-MHz band.

V. Conclusions

In this paper, we described the design method and experimental results of the periodic filter with a traveling-wave resonator. A lightweight band diplexer with 900-MHz 3-dB bandwidth for use on a communication satellite was fabricated in the 30-GHz band. Its weight is about 96 g and its dimensions are 15 × 9 × 4 cm. Measured insertion losses are 0.35–0.5 dB without plating. Relative delay time is less than 0.4 ns in $f_{1,2} \pm 300$ MHz. The experimental results demonstrate that this diplexer has improved frequency selectivity, wide-band characteristics, low insertion loss, and flat delay characteristics.

It is concluded that a periodic filter using a traveling-wave resonator can be used effectively in other branching networks, such as a guided millimeter wave transmission system and 20-GHz band radio relay communication system. This type of periodic filter can also be applied to stripline and beam waveguide filter systems.

Acknowledgment

The authors wish to thank Dr. K. Miyauchi, Dr. M. Shinji, and Dr. S. Shimada for their constant encouragement.

References

[1] W. L. Teeter and K. R. Bushore, "A variable ratio microwave power divider and multiplexer," *IRE Trans. Microwave Theory Tech.*, vol. MTT-5, pp. 227–229, Oct. 1957.
[2] R. A. Bromley and B. E. Callan, "Use of a waveguide dispersive line in an FM pulse-compression system," *Proc. IEE*, vol. 114, pp. 1213–1218, Sept. 1967.
[3] J. Bodonyi, "Channelling filter for trunk waveguide communication at millimetric wavelengths," *The Marconi Review*, third quarter, pp. 160–192, 1973.
[4] I. A. Ravenscroft and G. P. Kidd, "Improved commutating channel separator for millimetric waveguide systems," *Electronics Letters*, vol. 7, pp. 466–468, Aug. 12, 1971.
[5] S. Nishimura and T. Makimoto, "Improvement of frequency characteristics of preselector using a hybrid circuit," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 891–893, Oct. 1968.
[6] E. Kühn and R. Plegla, "Commutating microwave channel-separating filters with improved transfer characteristics," *AEÜ*, vol. 25, pp. 54–55, 1971.
[7] U. Unrau, "Periodic band-multiplexer for a TE_{01}°-telecommunication system," *AEÜ*, vol. 25, pp. 56–57, 1971.
[8] K. Miyauchi and I. Ohtomo, Japanese Patent 701606, Aug. 29, 1973.
[9] H. Kumazawa, I. Ohtomo, and S. Shimada, "30 GHz band periodic filter with a ring type resonator," *Trans. Inst. Elec. Commun. Eng. Japan*, vol. 59-B, pp. 55–62, Jan. 1976.