Design of a High-Power CW Y-Junction Waveguide Circulator

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Abstract—**A junction circulator appears inferior in average power-handling capability, although it is compact and light-weight, and has good performance. A new type of 100-kW CW waveguide Y-junction circulator is realized by dividing the junction of the circulator into four equal unit junctions in a so-called "multilayer structure," which is water-cooled easily. This circulator has an insertion loss of 0.18 dB and an isolation of 20 dB, and it is compact and economical to build. The design of 30- and 100-kW CW waveguide Y-junction circulators is presented in this paper, which discusses determination of ferrite dimensions and air gap, considers heat generation in the ferrite, and the influence of dc magnetic-field distribution on its performance. The ferrite dimensions and air gap are determined very easily by using this design method, and these have been confirmed by experiment. It was found that a uniform distribution of internal dc magnetic field, obtained by considering the demagnetizing dc magnetic field, gives optimum performance. This is a significant design factor for high-power circulators which require minimum insertion loss.**

I. Introduction

THE APPLICATION of high microwave power has become important for industrial processing. In such high-power systems a high-power isolator is indispensable to protect the high-power source from instability and destruction due to reflected power from the processing load. A resonance type isolator or a differential phase-shift or a junction type circulator with dummy loads may be considered for the high-power isolator in the system. The resonance type isolator, however, has a rather high insertion loss, typically 0.5–1 dB and poor isolation, about 10 dB at 915 MHz and 2450 MHz. The differential phase-shift circulator has disadvantages of high insertion loss, large size, and heavy weight. A conventional junction circulator seems inferior in CW power handling capability although it is compact, lightweight, and has good performance. A strip-line type high-power circulator with a power handling capability of 15 kW at 670 MHz has been demonstrated [1]. However, this device has coaxial output ports. In a high-power system for industrial processing, waveguides are commonly employed so that coaxial-to-waveguide adaptors are required. Even higher microwave CW power is needed in industrial applications for increased efficiency of industrial processes. Thus a high-power waveguide circulator is desirable for such systems. The construction of a 30-kW CW waveguide Y-junction circulator at 915 MHz [2], has been already reported by the authors. This circulator has metal cylinders protruding from the upper and lower surfaces of the waveguide Y-junction, on which thin ferrite disks are attached. The structure and performance of a new type of 100-kW CW junction circulator at 915 MHz have also been reported [3]. This circulator has a four layered structure each of which is nearly identical to the junction-structure in the 30-kW CW circulator. This circulator has an insertion loss of 0.18 dB including loss of the adjusting elements, an isolation of 20 dB, and is fairly compact and lightweight.

In this paper, the design of a high-power Y-junction waveguide circulator, especially the determination of ferrite dimensions and the influence of the dc magnetic field distribution on performance of a circulator, and some experimental results are described.

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II. Design of a High-Power Y-Junction Waveguide Circulator

The following considerations are important in designing a high-power CW Y-junction waveguide circulator.

A. Heat Generation in Ferrite

Temperature rise in the ferrite of a circulator due to insertion loss has the possible consequence of shifting the circulator performance characteristics from optimum and may lead to the destruction of the ferrite. Therefore, temperature rise must be minimized as much as possible, and cooling of the ferrite is necessary. For high efficiency in cooling, the ferrite disk must be thin, attached to a metal cylinder, and water-cooled through the wall of the metal cylinder. A temperature difference ΔT_f between both surfaces of the ferrite when one surface of the ferrite is held at constant temperature, is given by $\Delta T_f = t \cdot P_f/(2\lambda S)$ where P_f is the power dissipated in the ferrite, t and S are thickness and surface area of the ferrite, respectively, and λ is the heat-conduction coefficient. For a high-power circulator it is necessary that the value of t/S be as small as possible while still maintaining circulator action. Thin ferrite disks are attached onto the surfaces of the metal cylinders protruding from the top and bottom surfaces of the waveguide Y-junction. A cross-sectional view of the waveguide junction is shown in Fig. 1. By using this basic structure, a 30-kW CW Y-junction waveguide circulator has been realized. The structure has the following advantages.

1) Water-cooling of the ferrite can be done easily through the wall of the protruding metal cylinders. Heat generated in the ferrite can be removed efficiently.

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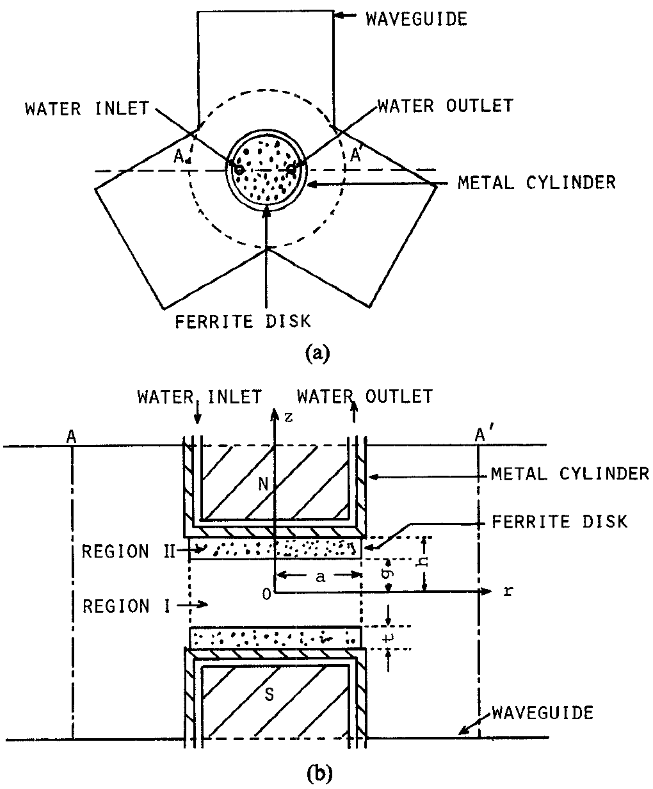

Fig. 1. Diagram of high-power Y-junction waveguide circulator. (a) Top view of the circulator. (b) Side view of the circulator.

2) The metal cylinder also serves as an impedance transformer and a reactive element [4] for adjusting the circulation action.

By inserting three additional metal disks at equal distances, as protruding metal cylinders, in the junction volume, and attaching thin ferrite disks onto both flat surfaces of the metal disks, the junction volume is divided into four equal portions, so that a multilayer junction is formed. The ferrite disks are water-cooled efficiently through the walls of the metal disks and cylinders. Each unit-junction has a power-handling capability of 30-kW CW so that a 120-kW waveguide junction circulator can be potentially realized.

Selection of the ferrite material is also important. Usually a ferrite material with a large spin-wave half-width is desired to avoid nonlinear effects, but in this circulator this factor is irrelevant because the circulator is operated in the above resonance region. Therefore a ferrite material suitable for a high-power circulator should have a narrow resonance half-width and low dielectric loss in order to reduce insertion loss, small saturation magnetization to reduce the applied dc magnetic field, and a large heat conduction coefficient to minimize temperature rise. Al-YIG ferrite material has a small heat conduction coefficient. Gd-YIG material has a large resonance half-width. Thus, in consideration of an optimized combination of the desired characteristics, a Bi-CaVG material was developed for high-power circulator applications [5], [6]. This material has a saturation magnetization of 4.9×10^{-2} Wb/m^2 and a resonance half-width of 6.4×10^3 A/m. For the material used, the radius a must be larger than 60 mm for a thickness of 4 mm, given ΔT_f of 30°C, an insertion loss of 0.2 dB and an input power level of 30 kW at 915 MHz. Considering the mechanical strength of ferrite disk, a thickness of 4 mm was selected for this circulator.

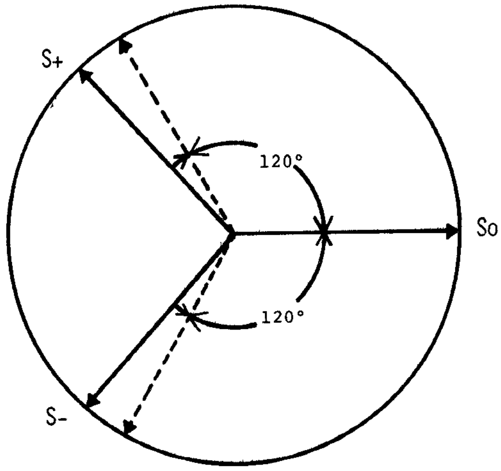

Fig. 2. Relationship of eigenvalues of S_+, S_-, and S_0.

B. Determination of Ferrite Dimensions and Air Gap

In this circulator, the region within the dotted portion in Fig. 1 is assumed to behave as a dielectric resonator which has a resonance frequency ω_+, ω_- for positive and negative circularly polarized wave excitation [7], [8]. At the operating frequency of $\omega=(\omega_+ + \omega_-)/2$, the relationship of eigenvalues S_+, S_-, and S_0, correspond to positive-, negative-, and in-phase excitations, respectively, is shown in Fig. 2, when looking from the plane A where S_0 lies along the positive real-axis. The angle between S_+ and S_- can be shifted to obtain circulation by adjusting the height of the metal cylinder operated as a transformer. For the 100-kW CW circulator, however, the angle can be varied by using additional transformers. The radius of the ferrite disk is determined by considering the permeability of $\mu_1=(\mu_+ + \mu_-)/2$ at the operating frequency ω. Then assuming the TM$_{nm}$ mode, the following relationships are obtained; regions I and II in Fig. 1 are ferrite and air regions, respectively. The potential function in each region is assumed as follows [1]:

$$\psi_{1n} = A_n[\cos k_{z1}(h-z)]J_n(k_\rho r)\exp(-jn\phi)$$
$$\psi_{2n} = B_n[\cosh k_{z2}z]J_n(k_\rho r)\exp(-jn\phi) \qquad (1)$$

$$E_{z1,2} = (k^2 - k_{z1,2}^2)\psi_{1,2} \qquad E_{r1,2} = \frac{\partial^2\psi_{1,2}}{\partial r\,\partial z}$$
$$H_{\phi_{1,2}} = -j\omega\epsilon\frac{\partial\psi_{1,2}}{\partial r}, \qquad n=\pm 1, \pm 2, \cdots \qquad (2)$$

where J_n is the nth-order Bessel function, g is one half of the distance between the metal cylinders, k_ρ is the propagation constant in the radial direction, k_{z1} and k_{z2} are the propagation constants in the longitudinal direction in the regions I and II, respectively, E_z and E_r are the longitudinal and radial components of electric fields, and H_ϕ is the

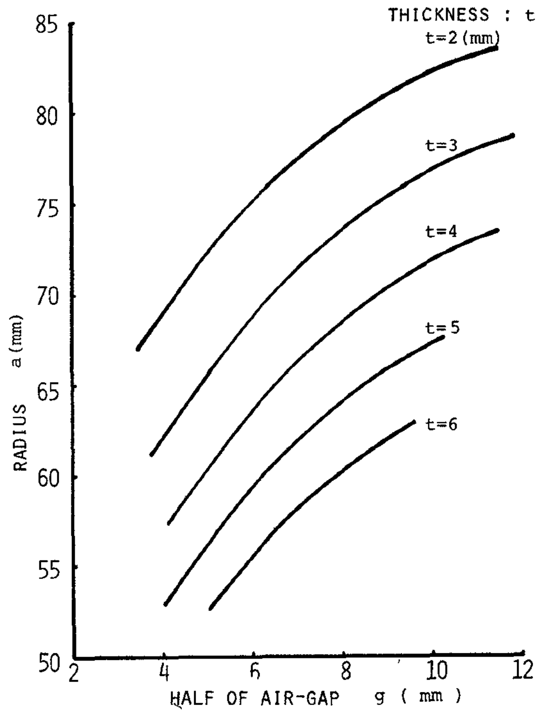

Fig. 3. Relationship of radius, thickness of ferrite disk and air gap (915 MHz, Bi-CaVG).

azimuthal component of the magnetic field. From continuity conditions of the surface impedance between regions I and II, by using equations (1) and (2) the following relationship is found:

$$\frac{k_{z1}\tan k_{z1}t}{\epsilon_1}=\frac{k_{z2}\tanh k_{z2}g}{\epsilon_2} \tag{3}$$

$$k_\rho^2+k_{z1}^2=\omega^2\mu_0\epsilon_0\mu_1\epsilon_1$$
$$k_\rho^2-k_{z2}^2=\omega^2\epsilon_0\mu_0 \tag{4}$$

where ϵ_0, μ_0 are the dielectric constant and the permeability of air and ϵ_1 is the specific dielectric constant in the ferrite. From (3) and (4), the following equation is obtained by assuming $k_{z1}t$ and $k_{z2}g \ll 1$:

$$\left(\frac{t^3}{\epsilon_1}+g^3\right)k_{z2}^4-\left(3g+3\frac{t}{\epsilon_1}+2\frac{t^3}{\epsilon_1}A\right)k_{z2}^2+\frac{t}{\epsilon_1}(3+t^2A)A=0 \tag{5}$$

where $A=\omega^2\mu_0\epsilon_0(\mu_1\epsilon_1-1)$.

In order to determine the radius of the ferrite disk, assume that the ferrite region operates as a cylindrical TM_{nm} mode resonator with $\mu_1=(\mu_+ + \mu_-)/2$, and $H_\phi=0(r=a)$, then

$$J_n'(\chi_{nm})=0 \text{ at } r=a \tag{6}$$

where a is the radius of the ferrite disk and $\chi_{nm}=k_\rho a$. Equations (3)–(6) give the relationship between radius a, thickness t of the ferrite disk, and half the air-gap distance g. The relationship between a and g for the ferrite material used at 915 MHz is plotted in Fig. 3 with t as the parameter, for $\mu_+=2.7$ and $\mu_-=1.5$ calculated from

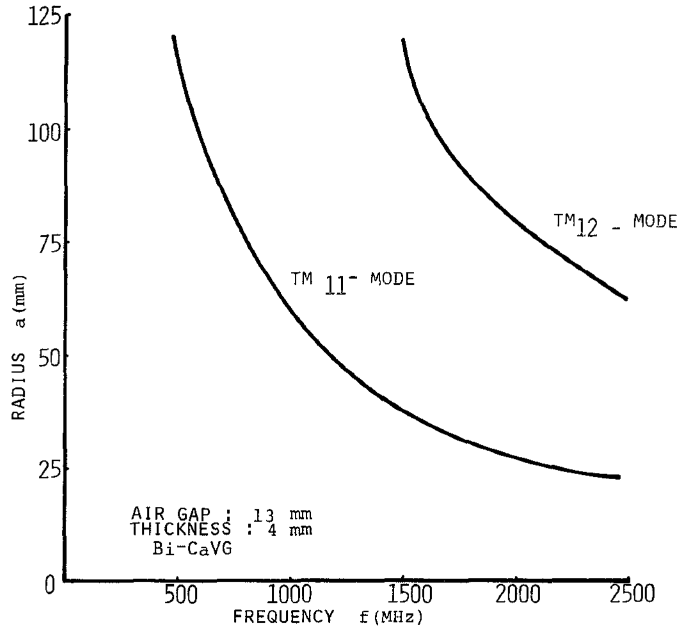

Fig. 4. Relationship of ferrite disk radius and frequency.

ferrimagnetic resonance [9]. This figure shows that the required dimensions of the ferrite disk are not unique at a fixed frequency, i.e., there is a wide range of dimensions. However, in a high-power circulator the range in dimensions is severely limited when also considering microwave breakdown, heat-generation in the ferrite, and mechanical strength of the ferrite.

From preliminary experiments, it has been confirmed that g of 6.5 mm is sufficient for microwave breakdown to occur at 30-kW CW power level at 915 MHz. In this high-power circulator, g is selected to be 6.5 mm, and t is selected to be 4 mm from consideration of its mechanical strength. From Fig. 3, a is determined as 64 mm considering the factors from Section II.

Equations (5) and (6) are functions of frequency. The ferrite radius a as a function of frequency for the fundamental (TM_{11}) mode and the second (TM_{12}) mode is given in Fig. 4 for a given ferrite size, thickness, and air gap. From the figure, the radius a is about 22 mm for the fundamental mode at 2450 MHz, so that this size of ferrite disk is not practical to operate at the 30-kW power level. For the second mode, however, the radius is 64 mm. Therefore, it has been found that there is a possibility of a 30-kW Y-junction waveguide circulator at 2450 MHz. This means that the power handling capability of 120-kW CW at 2450 MHz can be also potentially realized by using a multilayered configuration in the junction region.

C. Distribution of an Internal DC Magnetic Field in the Ferrite Disk

The influence of dc magnetic-field distribution in the ferrite disk on performance of the circulator is discussed here.

In designing a conventional circulator, it is usually assumed that an internal dc magnetic field of a ferrite disk in the direction of an applied dc magnetic field has uniform distribution independent of a distance from the center of the disk. It is, however, not uniform in practice due to the demagnetizing field which is a function of distance from the disk center. For a low-loss circulator, this effect must be considered. The demagnetizing field H_d of a ferrite disk in the central plane of the disks, magnetized perpendicular to its plane, is given by [10]

$$\frac{H_d(r)}{M_0} = -1 + \left[\frac{t/D}{\left[1+(t/D)^2\right]^{1/2}} + \frac{3t/D}{\left[1+(t/D)^2\right]^{3/2}} - \frac{3(t/D)^3}{\left[1+(t/D)^2\right]^{5/2}} \right] \left(\frac{r}{D}\right)^2 \quad (7)$$

near the central region of the disk, and by

$$\frac{H_d(r)}{M_0} = -\frac{1}{2} - \frac{1}{\Pi} \tan^{-1}\left[\frac{(D-2r)}{t}\right] \quad (8)$$

near the edge of the disk. Here $H_d(r)$ is the demagnetizing field, D is the diameter of the ferrite disk, and r is the distance from the center of the disk in the central plane. A curve of $H_d(r)$ is connected smoothly by plotting equations (7) and (8) for the case of a strong applied dc magnetic field.

The performance of the circulator is measured for three types of distribution of the applied field by varying the shape and size of the pole piece of an electromagnet. Three shapes of pole pieces are used: 1) shape A—a flat top with a radius slightly larger than the ferrite disk radius, 2) shape B—a flat top and a slightly smaller radius, and 3) shape C—a rounded-off top and an even smaller radius. Internal fields H_i for shapes A, B, and C calculated from equations (7) and (8), have distributions of A, B, and C, respectively, in Fig. 5(a). A uniform distribution can be obtained by using shape B pole piece. The insertion loss and isolation for shapes A, B, and C are shown in Fig. 5(b). This preliminary experiment shows that the insertion loss and the isolation are improved by applying the internal dc magnetic field uniformly.

III. Experiments on 30-kW and 100-kW CW Y-Junction Waveguide Circulators

The structure of a 30-kW CW Y-junction waveguide circulator is shown in Fig. 1. The height of a WR-975 waveguide was reduced to one-half of its original value. The dimensions of the ferrite used are those given in Section II. The ferrite disks are attached to the flat-surfaces of the iron disks and the metal cylinders by using a silicon-rubber adhesive. The dc magnetic field is about 7.9×10^4 A/m in order to operate in the above-resonance region which avoids nonlinear effects, and is supplied by barium ferrite disks for compactness and cost efficiency. The eigenvalues of the circulator were measured by using the method described by Owen [11]. The eigenvalues of the circulator are modified slightly by the transformer action of the metal cylinders. The experimental results show that the insertion loss of the circulator is less than 0.1 dB, the isolation more than 20 dB, and the input VSWR below 1.2 at 915±25 MHz for power levels up to 30 kW. The circulation characteristics have been maintained stably up to 30-kW CW power level for all phases of a short-circuited load. The temperature rise in the ferrite disks is kept below 10°C at 30-kW CW input power level, when the water flow rate is about 1.2 l/min per ferrite disk. These experimental results indicate that this design approach is useful for a high-power circulator. The four-layered structure of the higher power 100-kW CW waveguide Y-junction circulator is shown in Fig. 6. The waveguide is full size WR-975. In the circulator, the metal disks are made from iron in order to obtain a uniform internal dc magnetic field in the ferrite disks. The iron disks are copper-plated to reduce insertion loss. Three iron disks, placed at equal distance from each other, are supported by thin metal pipes. The pipes serve as conduits for the running water in order to cool the ferrite disks. The edge of the iron disk is rounded off to obtain uniform distribution of the internal dc magnetic field. The power handling capability of the circulator is the sum of that for

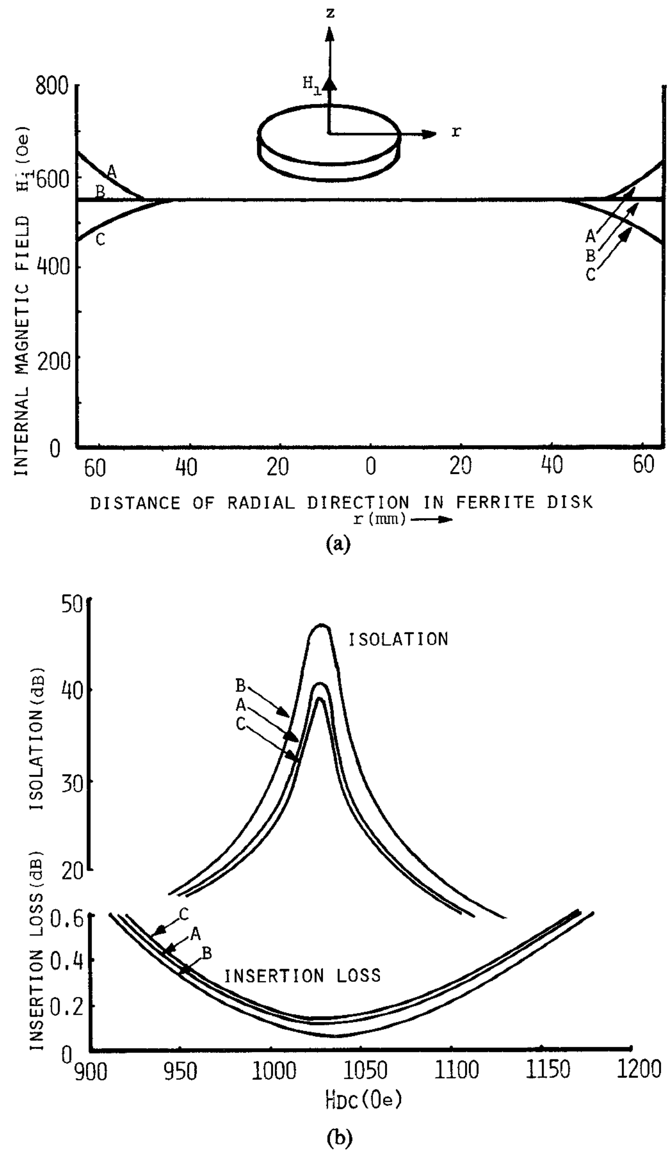

Fig. 5. Distribution of magnetic field and circulator characteristics. (a) Distribution of internal dc magnetic field. (b) Influence of magnetic field on circulator characteristics.

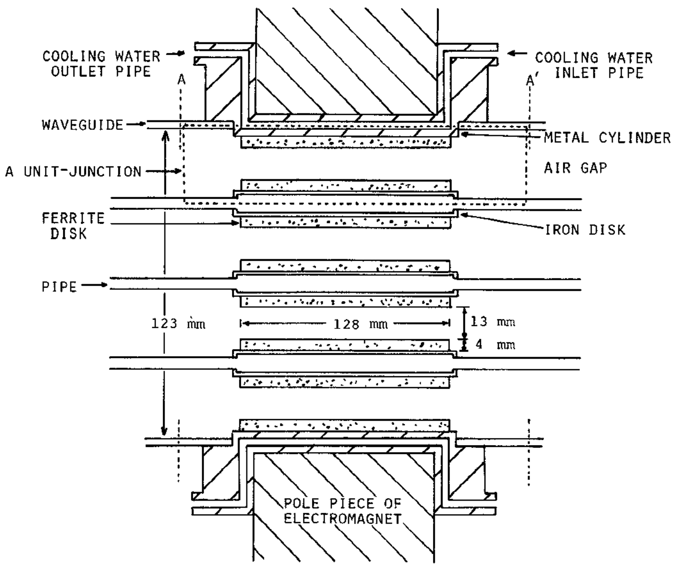

Fig. 6. Diagram of 100-kW CW circulator.

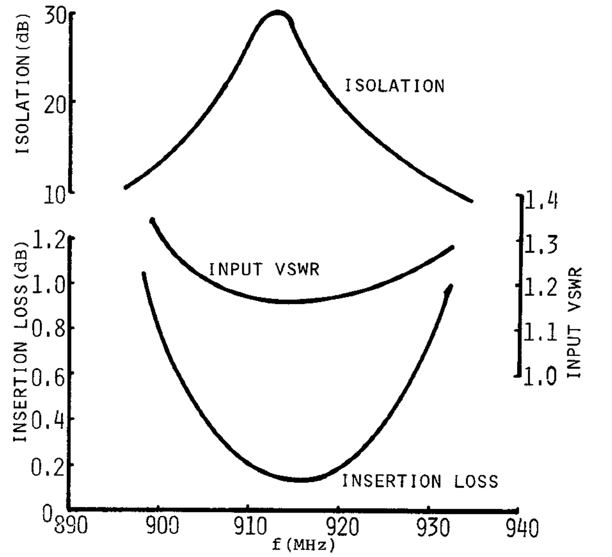

Fig. 8. Frequency characteristics of 100-kW CW circulator at low power level.

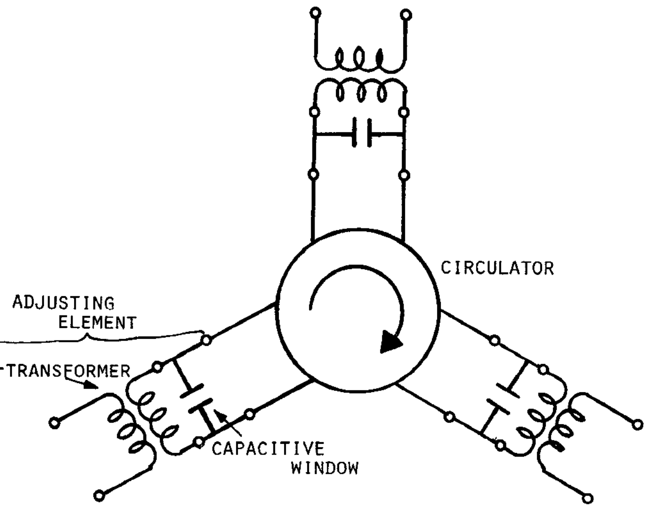

Fig. 7. 100-kW circulator and adjusting elements.

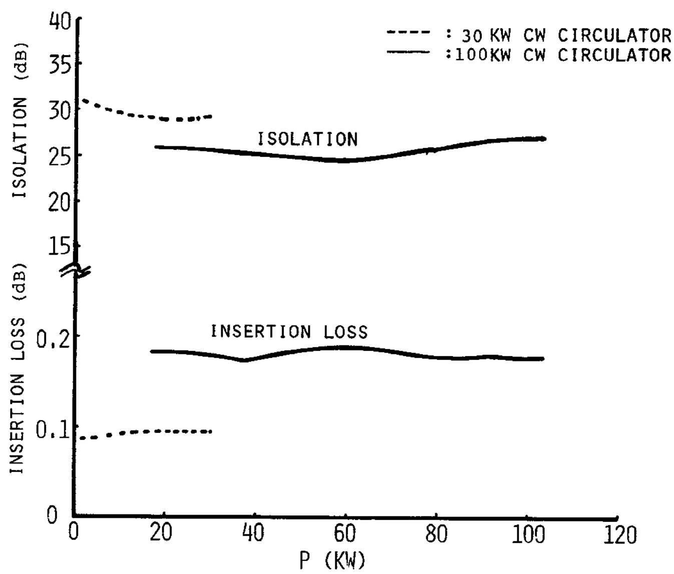

Fig. 9. High-power characteristics of circulators.

each unit-junction layer, and one layer is shown bound by a dotted line in the figure. Each layer has nearly the same design as the one used in the 30-kW circulator. The capability of the circulator with the multilayer structure is potentially 120-kW CW at 915 MHz. The ferrite disks used have the same dimensions as those of the 30-kW circulator. The applied dc magnetic field is supplied by an electromagnet. The eigenvalues, measured without the adjusting elements, show somewhat different values from the ideal ones needed for circulation. The eigenvalues are adjusted by using capacitive windows and $\lambda/4$ transformers made from metal blocks to avoid microwave breakdown which are connected at each port of the circulator as shown in Fig. 7. After adjusting the elements, the eigenvalues approached the nearly ideal ones. The performance of the circulator at low power level is shown in Fig. 8. This shows that the insertion loss is less than 0.18 dB and the isolation larger than 20 dB at 915 MHz. The loss due to the ferrite itself is about 0.11 dB. The bandwidth of the circulator is rather narrow. This is due to the frequency characteristics of the adjusting elements. The circulator bandwidth can be improved by broadbanding the adjusting elements. The experimental results at high power levels are shown in Fig. 9. The circulator has performed stably for any phase of an output port shorted load up to 100-kW power level. The mean temperature rise of ferrite disks was about 6°C. The relative deviation of the temperature rise among different disks was less than 8 percent of this mean value and was within experimental error. Thus one may conclude that the temperature of the disks is uniform within experimental error. Therefore one can say that the metal disks divide equally the input power to the circulator. The size of the 100-kW circulator including those of the adjusting elements and the electromagnet is about 1 m in length and 0.5 m in height, and the total weight is 120 kg.

IV. Conclusion

A 30-kW CW waveguide Y-junction circulator at 915 MHz has been realized with protruding metal cylinders into the waveguide junction, with thin ferrite disks on their flat surfaces. On the basis of this result, a 100-kW CW waveguide Y-junction circulator was developed by inserting three additional metal disks within the junction region, and by attaching ferrite disks on each surface of the water-cooled metal disks. Each ferrite disk is water-cooled efficiently and the input power to the circulator is divided equally by a multilayer structure.

The design of a 100-kW CW waveguide Y-junction circulator at 915 MHz was obtained by analyzing the relationship between the ferrite dimensions and the air-gap considering power dissipation in the ferrite. The dimensions of the ferrite disk and the air-gap were determined very easily, and the utility of this design technique was confirmed experimentally. It was found that the internal dc magnetic-field distribution influences the performance of the circulator.

This approach was found to be very important for designing high-power circulators which require low insertion loss. The 30-kW and 100-kW Y-junction circulators have good performance, are compact and can be built economically. The results indicate that a 100-kW CW waveguide Y-junction circulator at 2450 MHz and at other frequencies can be realized by using this type of configuration.

Acknowledgment

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Generation of Microwave Power with a Spark-Gap Cavity

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***Abstract*—A theory of a $\lambda/4$ transmission line resonator containing a spark gap is developed and parameters such as output spectrum, bandwidth, Q factor, and efficiency are derived. Equivalent circuits incorporating different spark-gap parameters are presented and used for numerical simulation of cavity output. Several fixed and variable frequency cavities are constructed and tested. Typical peak power outputs are 7.2 kW into 50-Ω line at a frequency of 2.1 GHz, and 27 kW into 50-Ω line at a frequency of 1.5 GHz. For proper operation of this device the spark resistance must fall to a value less than the characteristic impedance of the line in a time less than T where $f_0 = 1/2T$ is the required frequency.**

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I. Introduction

SPARK GAP switches are well known as they have been used in radar equipment for many years as