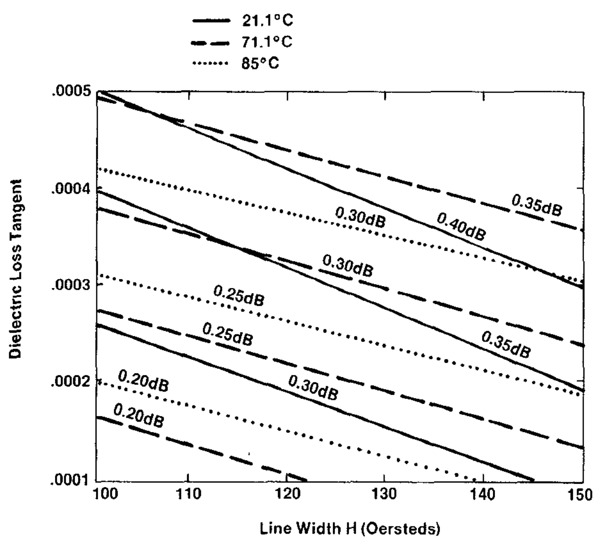

Fig. 6. Insertion loss versus linewidth and loss tangent.

parameters consistent with high average-power capability in such isolators has been calculated by using the perturbation approach to ferrite-loaded waveguides [1]. The ferrite in question is a NiAl ferrite selected for low loss. Typical values of dielectric loss tangent (tan δ) and line width (ΔH) are 0.0005 and 120 Oe, respectively. Fig. 6 shows insertion loss as a function of line width ΔH and loss tangent for three temperatures. It is clear that keeping insertion loss below 0.25 dB in high-power conditions in which the ferrite slabs heat up due to RF absorbed power, requires a dielectric loss tangent below about 0.0003 and line widths of 120 Oe. The ferrite used in these circulators had line widths of 120 Oe and loss tangent values less than 0.0004.

V. Conclusion

We have proposed and substantiated a mechanism by which high-power ferrite circulators and isolators suffer apparent "arc destruction." The failure mechanism, which is initiated with hard epoxy adhesive layer rupture, can be eliminated by using a highly flexible silicone adhesive. A range of ferrite material parameters consistent with high average-power S-band operation is computed.

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A 50-kW CW Ferrite Circulator in *S* Band

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***Abstract*—A 50-kW CW differential phase-shift circulator at 2450 MHz has been developed. Its insertion loss and isolation are 0.18 dB and 20 dB, respectively, over a bandwidth of 25 MHz at 2450 MHz. It is useful for protecting the microwave source of a high-power system from reflected power. The design and experimental results of the circulator are presented.**

I. Introduction

Microwave power has been successfully used for industrial applications. In France, we tend to use higher and higher power sources at 2450 MHz, and, in particular, a 50-kW CW Thomson CSF klystron. In such a system, an isolator or a circulator is indispensable to protect the high-power source from reflected power.

At this frequency range, a Y-junction circulator is still inferior in power handling capability although this capability is increasing recently. At these power levels, the approach commonly used consists of a four-port differential phase-shift circulator. To reduce the power level received by the ferrite material, we can use either 3-dB couplers or 8.34-dB couplers in tandem [1]–[3].

In our research on a 2450-MHz 50-kW CW circulator, we have taken into account the two above mentioned approaches. This paper presents the realized structures and the design and performance of a 50-kW CW ferrite circulator at 2450 MHz.

Manuscript received April 14, 1978; revised September 13, 1977. This work was supported by the Direction des Recherches et Moyens d'Essais.

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II. Design of a High-Power Ferrite Circulator

The classical differential phase-shift circulator [4] uses a folded magic tee and a 3-dB coupler. Between those two

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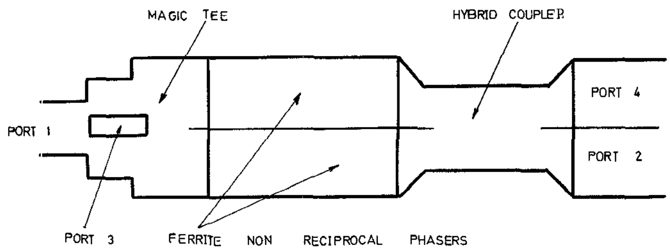

Fig. 1. Differential phase-shift circulator.

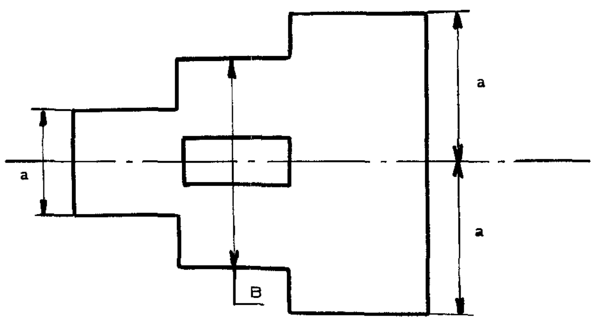

Fig. 2. Magic tee.

components, we have a dual ferrite cell; the differential phase shift is ±90° for each port of the cell. In this approach, each ferrite material receives half of the incident power (Fig. 1).

The second approach consists of two reciprocal and nonreciprocal phase shifters inserted between 8.34-dB couplers and a 3-dB coupler. The differential phase shift is equal to ±180° in this case and the first ferrite cell receives one seventh of the incident power [1], [2].

In this frequency range, we noticed that no component existed commercially; consequently, we had to study each element of the circulator: the standard waveguide is the RG 112/U (WR 340) and the frequency range is 2450 MHz±25 MHz.

We will review successively each of the circulator components.

A. Magic Tee

According to the general scheme, shown in Fig. 2, we require that, at the input on the left, we have the fundamental TE_{10} mode and at the two outputs on the right we also have the fundamental TE_{10} mode.

From these considerations, it was possible to define the intermediate zone in which is located the difference port. We calculated the B dimension so that only the fundamental TE_{10} mode passed through without having a higher mode appearing.

Low-level measurements of the device show a voltage standing wave ratio (VSWR) appearing on the sum and different ports not exceding 1.1. The isolation between these two ports is 42 dB.

B. Couplers

1) Hybrid 3-dB Coupler: After a study of the possible couplers, we retained a Riblet [5] type coupler. Its performance at low level is VSWR is 1.14 and isolation is 24 dB.

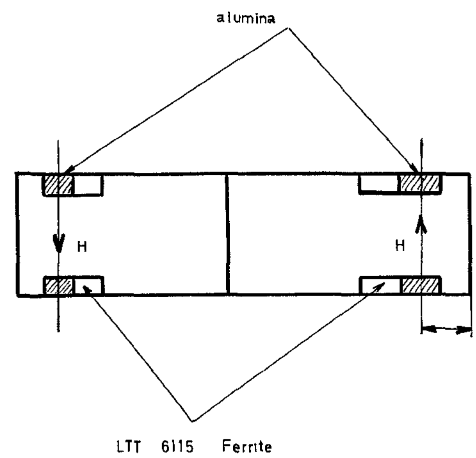

Fig. 3. L.T.T. 6115 ferrite cell.

2) 8.34-dB Coupler: We preferred to use a multiwaves guide coupler. The theory is based on Chebyshev filters made by Levy [6]. A prototype was realized in our department. The low-level performances indicated that the coupling remained constant and equalled 8.34 dB within the frequency range of 2450 MHz±50 MHz. The directivity was about 40 dB on this same frequency range.

C. Nonreciprocal Ferrite Phase Shifters

1) Phase Shift of $\Delta\beta = \pm 90°$: The phase-shift cell is a ferrite loaded waveguide cell whose differential phase shift is ±90°. The ferrites are those from the Lignes Télégraphiques et Téléphoniques (L.T.T.) firm. Our department studied the phase-shift cells from a choice of 2 ferrite materials. 6115 and 6303 are garnet of gyralite type —the 6115 is a nickel manganèse garnet ferrite and 6303 a magnesium garnet ferrite.

	6115	6303
$4\pi M_s$	500 G	750 G
g_{eff}	1.55 G	1.98 G
ΔH	150 Oe	120 Oe
ΔH_K	12 Oe	6 Oe
ϵ'	9	11.3
$\tan\delta$	8×10^{-4}	2.5×10^{-4}
T_C	120°	90°

Experiments have shown that the 6115 ferrite is better with respect to average power capability.

We have used a structure with two ferrite heights. The maximum figure of merit was obtained when an alumina dielectric slab was placed near the ferrite materials (Fig. 3) [4], [7].

The cell has a phase shift of 5.7°/cm and an attenuation of 0.008 dB/cm (Figs. 4 and 5).

The phase shifters are adjusted to obtain at a maximum 50-kW CW power, a differential phase shift near 90°. This adjustment was deduced after simulation of the heating process of phase-shift cells in ovens. The phase shift is equal to 110° at a low-power level.

2) Phase Shift of $\Delta\beta = \pm 180°$: The length of this phase shifter is twice the previous one. The total insertion losses will then be 0.3 dB against 0.15 dB.

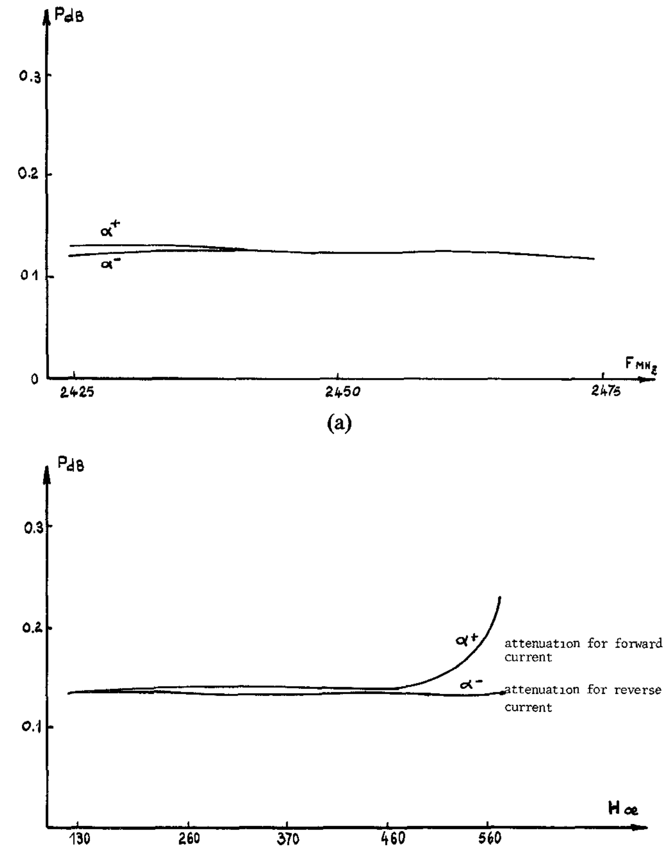

Fig. 4. (a) Insertion losses versus frequency for ferrite-phaser cell $\Delta\phi = 90°$. (b) Insertion losses versus magnetic field for ferrite phaser cell at $\Delta\phi = 90°$.

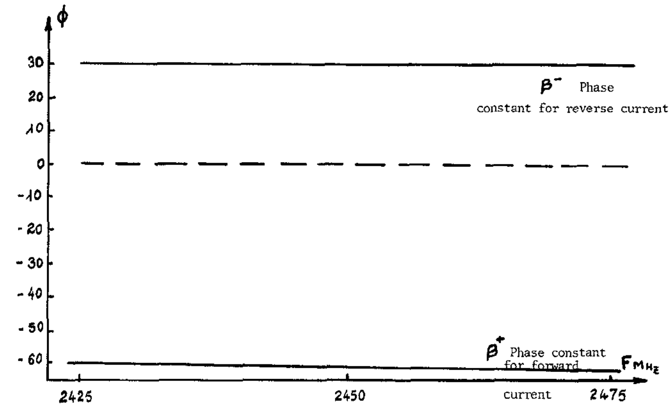

Fig. 5. Phase shift versus the frequency ferrite-phase cell.

III. Choice of the Circulator Type

The circulator using a 8.34-dB coupler and a 180° phase shifter was put aside for the following reasons.

1) The phase-shifter length is double, therefore the permanent magnets are longer. The weight, length, and price are therefore increased.

2) Although the isolation would have been greater, the insertion losses would have been too high.

We therefore preferred the circulator using the magic tee. The latter was treated at low level, then at high level.

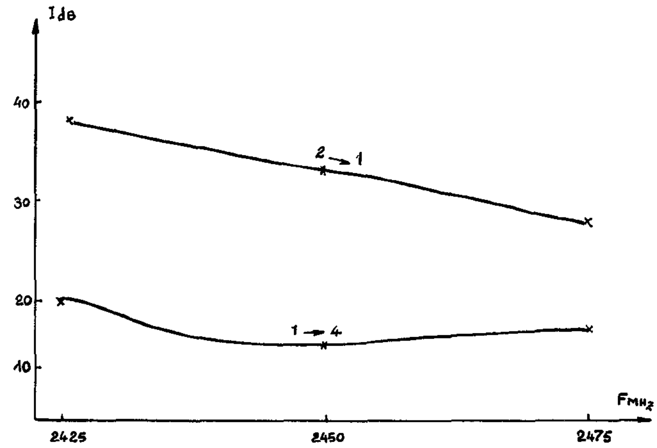

Fig. 6. Isolation versus frequency for the circulator low level.

IV. Performance of the Differential Phase-Shift Circulator

A. Low-Level Performances

According to Fig. 1, we measured the following characteristics.

1) VSWR: At input port 1, the VSWR is a 1.22-constant over the band. At port 2, it varies from a maximum of 1.16 and a minimum of 1.02.

2) Insertion losses: The insertion losses on ports 1 and 2 are constant and equal to 0.34 dB. From port 2 to port 3 they are also constant and equal to 0.23 dB.

3) Isolation: Isolation from port 2 to port 1 is 38 dB at 2525 MHz and 28 dB at 2475 MHz. Isolation from port 1 to port 4 is 20 dB at 2525 MHz and 15 dB at 2425 MHz (Fig. 6).

At low level, the insertion losses from port 1 to port 2 are relatively important and the isolation from port 1 to port 4 is weak. This is due to the fact that phase shifters have a 110° differential phase shift. The performances become maximum for a 50-kW CW input power because the ferrite heating reduces the $4\pi M_s$ then the phase shift equals 90°.

B. High-Level Performances

To reduce the insertion losses and avoid any breakdown field phenomenon, the following precautions have been taken.

1) All mechanical pieces are silvered inside with a 6-μm layer, then they are gilded with a 1-μm layer to avoid silver sulphuration.

2) All areas were eliminated where eddy currents were impeded by obstructing them with a polymer silver paste at 100° C.

3) All corners were rounded to increase the power capacity and avoid any problem of arc phenomenon.

4) Matching is realized by inductance posts.

5) To increase the thermal exchange with ambient air, the circulator is painted in dull black. Furthermore, the

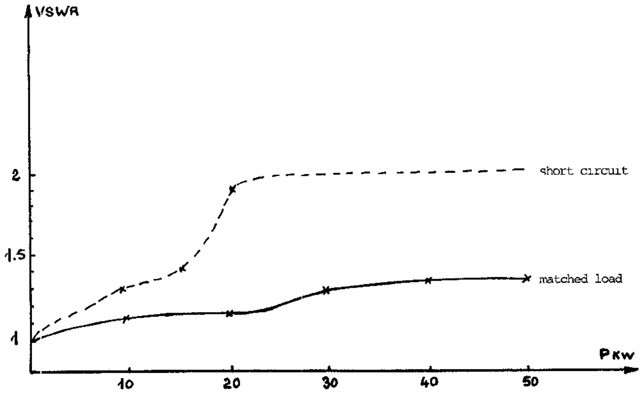

Fig. 7. VSWR versus power level for circulator at $F=2450$ MHz.

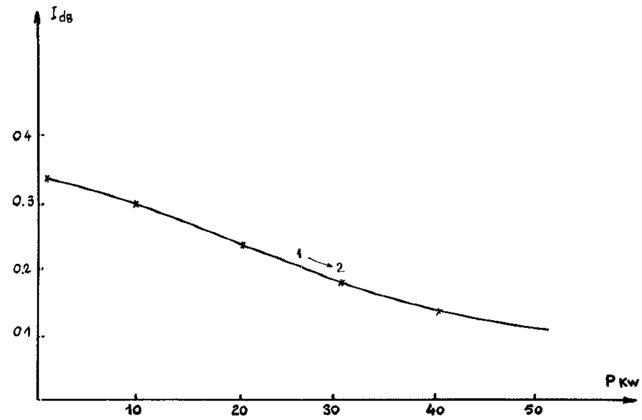

Fig. 8. Insertion losses versus power level.

ferrite phase shifters are cooled by flowing water (8 l per min).

Within these conditions, the high-level circulator performances are measured with the use of water calorimeters. The performances are then listed as follows.

1) VSWR: The VSWR is the same as at low level when the circulator is terminated in a matched load. If the load is a short-circuit, the VSWR increases slightly and becomes equal to 1.9 at 50-kW CW (Fig. 7).

2) Insertion losses: Once the adjustment is made on the ferrite phase shifters, we noticed that the more the power increased, the more the insertion losses were reduced to become equal to 0.12 dB from port 1 to port 2 at 50-kW CW (Fig. 8).

3) Isolation: For the same reason as above, isolation of port 1 to port 4 increases with the power to equal 32 dB (Fig. 9).

V. Conclusion

We defined a ferrite circulator prototype operating at 2450 MHz ± 25 MHz capable of handling 50-kW CW into a matched load or into a full short-circuit of any phase [8].

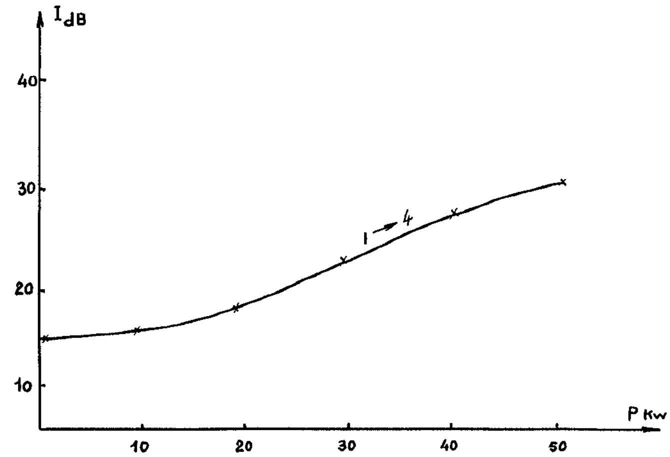

Fig. 9. Isolation versus power level at $F=2450$ MHz for the circulator.

The total dimensions of the device are

length 1 m,
width 0.30 m,
height 0.20 m,
weight < 70 kg.

The main performances are

average insertion losses 0.2 dB,
isolation between ports > 20 dB,
VSWR < 1.3,
theoretical peak power limitation approximately 2 MW.

This device is being industrialized at the L.T.T. firm.

Acknowledgment

The authors wish to thank Mr. Salomon and Mr. Faillon for their useful discussions and for allowing us to make experiments on their equipment.

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