Millimetric Nonreciprocal Coupled-Slot Finline Components

LIONEL E. DAVIS, SENIOR MEMBER, IEEE, AND DAVID B. SILLARS, MEMBER, IEEE

Abstract —**Promising preliminary results are presented for isolators and a four-port circulator in novel finline structures in the frequency range 26.5–40.0 GHz. The basic configuration is a ferrite-loaded coupled-slot finline with the ferrite magnetized parallel with the direction of propagation. The nonreciprocal effects of the odd mode propagating alone and of the odd and even modes propagating are described. All structures exhibit a 20-dB isolation bandwidth greater than 3.6 GHz. It is suggested that such structures would also be suitable for higher frequencies.**

I. Introduction

THE EASE of fabrication of finline technology together with its applicability at millimeter-wave frequencies has resulted in some effort to produce nonreciprocal devices [1], [2]. However, for traditional nonreciprocal structures (junction circulators, resonance isolators, etc.,) operating at millimeter-wave frequencies, a strong magnetic bias field or an anisotropic ferrite would normally be required together with a ferrite sample which is physically small and machined to close tolerances.

Nonreciprocal finline structures are reported here in which a) rectangular ferrite slabs are magnetized longitudinally enabling saturation to be achieved from weak magnetic fields due to the small demagnetizing factor, b) hexagonal ferrites are not required, and c) nonreciprocity is developed with a "large" slab, i.e., over several wavelengths, rather than a fraction of a wavelength as in traditional junction devices.

II. Reciprocal Structures

The finline structures considered are shown in Fig. 1(a) and (b). They consist of a ferrite slab placed either on the conductor surface (sandwich-layer) or on the substrate surface (double-layer) of the finline circuit. Two parallel slots etched from the copper conductor produce the guiding structure.

In the unmagnetized isotropic case, the double substrate coupled-slot finlines can support two propagating modes, the odd and even modes. In accordance with the convention adopted in [3], the odd mode is defined here as having the electric field E_y an even function of y with respect to the x-axis and even mode having E_y an odd function of y with respect to the x-axis. Fig. 2(a) and (b) show the electric fields of both modes in the air and dielectric regions. The odd- and even-mode dispersion characteristics of a typical double-dielectric substrate coupled-slot finline are shown in Fig. 3. These results were computed using the transverse resonance technique as applied to finlines [4], [5].

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The authors are with the Department of Electrical and Electronic Engineering, Paisley College of Technology, Paisley, PA1 2BE, Scotland.
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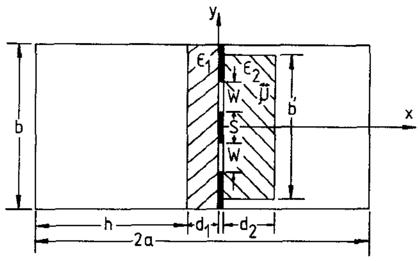
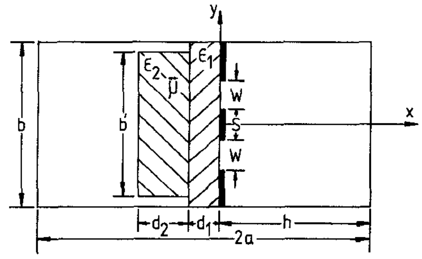


(a)



(b)

Fig. 1. Ferrite-loaded coupled-slot finline. (a) Sandwich-layer structure. (b) Double-layer structure. $a = b = 3.556$ mm, $b^1 = 3.0$ mm, $\epsilon_1 = 2.22$, $\epsilon_2 = 13.0$, $d_1 = 0.127$ mm, $d_2 = 0.5$ mm, $h = 3.4925$ mm, $M_s = 4000$ A/cm.

The nonreciprocal properties of these structures will now be described for the cases where only the odd mode is launched alone and where both the odd and even modes are launched.

III. Nonreciprocal Behavior

Preliminary results for a coupled-slot finline isolator have recently been described [6], [7]. It was reported that when a coupled-slot finline loaded with a ferrite slab (Fig. 1(a)) and supporting only the odd mode was magnetized parallel with the direction of propagation, a displacement of the field from one slot to the other occurred. Excitation of the odd mode was achieved by a transition from a unilateral single-slot finline taper into the coupled-slot region via a tapered center conductor. The insertion loss for two back-to-back waveguide to finline tapers plus

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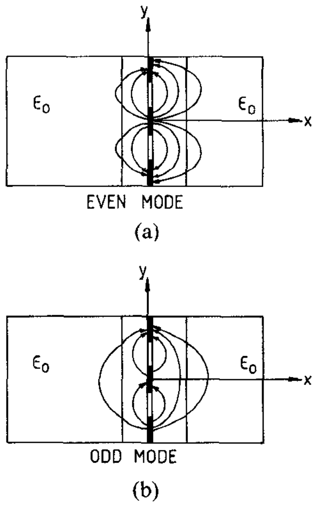

Fig. 2. Electric-field distribution of the dielectric sandwich-layer coupled-slot finline for (a) even-mode and (b) odd-mode excitation.

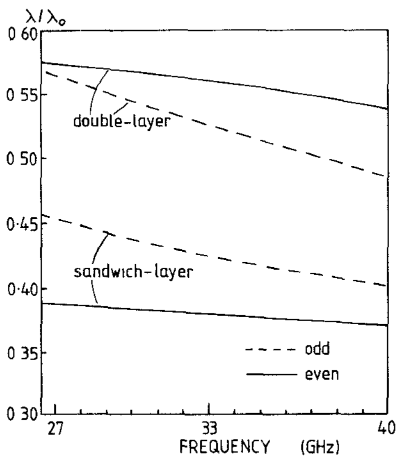

Fig. 3. Dispersion characteristics of even and odd modes in dielectric double-layer and dielectric sandwich-layer coupled-slot finline. $W = S = 0.5$ mm, $\epsilon_1 = 2.22$, $\epsilon_2 = 13.0$, $d_1 = 0.127$ mm, $d_2 = 0.5$ mm.

single-slot to coupled-slot transitions separated by a coupled-slot section of 28 mm in length is better than 0.4 dB over the 26.5–40.0-GHz frequency band.

The field displacement phenomenon was observed in a coupled-slot finline in which one slot incorporated a bend to permit waveguide detectors to monitor each slot separately. Fig. 4(a) and (b) show the nonreciprocal change in power that occurred in each slot for the sandwich-layer and double-layer structures for both directions of the applied magnetic field. In the diagrams, 0 dB corresponds to the output power at each slot for zero applied magnetic field. The lack of symmetry in the amount of shifting may be attributable to the bend in the finline circuit. These graphs show that, with a fixed direction of bias field, the nonreciprocity is reversed by moving the ferrite slab from one side of the finline plane to the other. They also show that in the double-layer structure the ferrite produces weaker nonreciprocity because it is in a region of weaker field [8]. It was also observed that once the ferrite was saturated there was no further change in performance as the applied field was increased, bearing in mind that it was still far below that required for ferrimagnetic resonance.

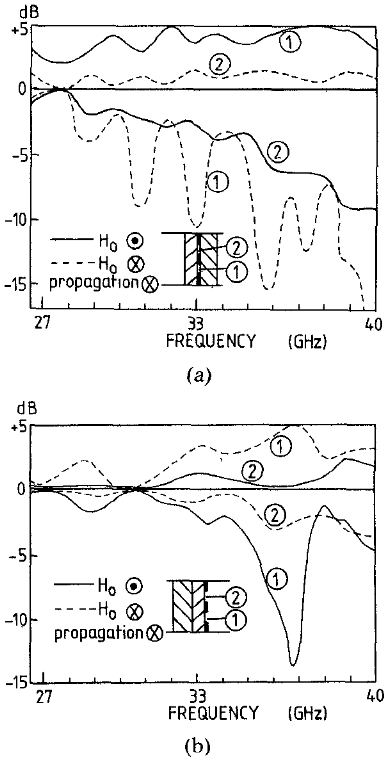

Fig. 4. Signal difference curves for each slot port and direction of H_0 for (a) ferrite-dielectric sandwich-layer structure and (b) ferrite-dielectric double-layer structure. Each characteristic is shown with respect to its own (0 dB) reference level which was obtained with the ferrite unmagnetized. $W = S = 0.5$ mm, ferrite length $= 14.0$ mm, $H_0 = 400$ A/cm.

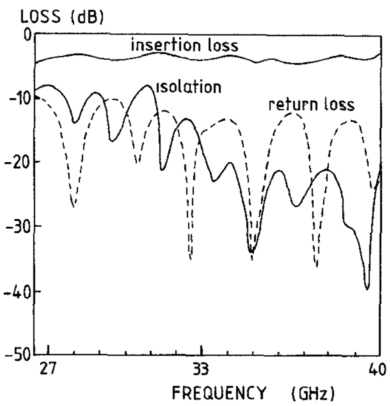

Fig. 5. Performance of single ferrite coupled-slot finline isolator. $W = S = 0.5$ mm, ferrite length $= 14.0$ mm, $H_0 = 400$ A/cm.

IV. Isolators

One application of this phenomenon is in an isolator, produced by placing a piece of resistive card over one slot. Fig. 5 shows results for insertion loss, return loss, and isolation for the case where a dielectrically-matched ferrite slab was placed on the conductor surface and magnetized parallel to the direction of propagation. The isolation was measured by reversing H_0, and the broad-band potential of this structure is evident.

TABLE I
CHARACTERISTIC IMPEDANCE IN Ω OF RECIPROCAL COUPLED-SLOT FINLINE STRUCTURES

Unloaded line	Sandwich-layer dielectric (ferrite) line	Matching impedance	Matching dielectric-loaded line
178	117	144	147

$W = S = 0.5$ mm, dielectric (ferrite): $\epsilon_2 = 13.0$, $d_2 = 0.5$ mm, matching dielectric: $\epsilon_2 = 3.0$, $d_2 = 1.0$ mm.

TABLE II
WORST CASE RESULTS OVER FREQUENCY RANGE 26.5–40.0 GHz

Fin-line circuit configuration	Insertion loss (dB)	Return loss (dB)
unloaded	0.4	16.0
with unmagnetised ferrite (1)	4.5	4.5
with ferrite (1) and matching-dielectric	2.2	13.0
with tapered ferrite (2)	3.0	10.0

$W = S = 0.5$ mm. Ferrite ①: 14 mm long, dielectrics: $\epsilon_r = 3.0$, 1.5 mm long. Ferrite ②: 20 mm long with 5 mm long tapers.

A. Dielectric Matching of Ferrites

The discontinuity produced at the ends of the ferrite slab was reduced by the use of low-permittivity quarter-wavelength dielectric sections. These sections were designed to match, ideally, at 33.5 GHz using the transverse resonance technique [4], [5]. The unmagnetized isotropic ferrite-loaded finline structure was simulated by a double-dielectric sandwich-layer substrate finline to permit calculation of the odd-mode characteristic impedance. Table I shows the characteristic impedance for the unloaded and dielectric (ferrite)-loaded finline and the matching section which was obtained using standard transmission-line theory. Also quoted is the characteristic impedance of the resultant matching dielectric-loaded section. This value is a function of the dielectric permittivity and its thickness as well as the finline characteristics. Therefore, the same value of characteristic impedance can be obtained for different combinations of these parameters. However, the choice of dielectrics used was limited to what was at hand resulting in a dielectric with a permittivity of 3.0 being chosen to give the nearest impedance.

Table II gives results of insertion loss and return loss for the unloaded, unmagnetized ferrite-loaded and the ferrite/dielectric finline circuits. Also given are results for the finline circuit loaded with unmagnetized tapered ferrites which were used in the devices described in the following sections.

B. Twin Ferrite Arrangement (Anti-Parallel Fields)

The investigation was extended to study the effects of placing two ferrite slabs on the coupled-slot finline separated by a length of resistive card placed over one slot. Nonreciprocity was produced by magnetizing the ferrites with anti-parallel magnetic fields, achieved by placing a bar magnet alongside each ferrite region. The small longitudinal field produced by each magnet was sufficient to saturate the ferrite slabs. Fig. 6 shows the structure with the ferrites and resistive card tapered at each end to help reduce losses and results are shown in Fig. 7. It can be seen that a maximum isolation of 41.5 dB is obtained with a 20-dB isolation bandwidth of 6.75 GHz (18.4 percent) together with insertion losses of between 3.5–6.0 dB and a return loss better than 16 dB over the 20-dB isolation bandwidth.

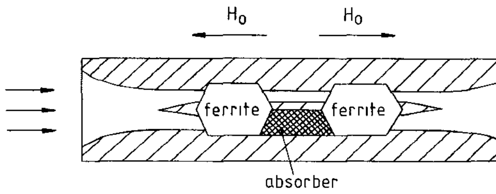

Fig. 6. Coupled-slot finline with two ferrite slabs magnetized in opposite directions and separated by a length of resistive card. With the input and the static fields directed as shown, the device exhibits isolation.

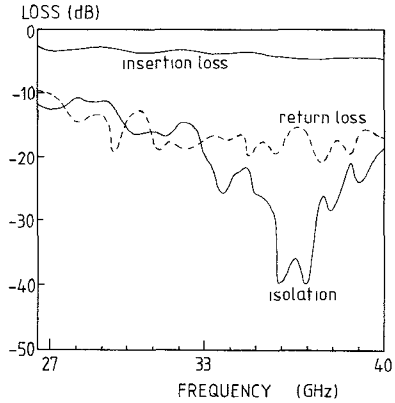

Fig. 7. Performance of twin ferrite coupled-slot finline isolator. $W = S = 0.5$ mm, ferrite length = 20 mm, $H_0 = 160$ A/cm.

For the same isolator structure, but using dielectrically-matched ferrite slabs [6], the 20-dB isolation bandwidth was measured to be 3.8 GHz (13.0 percent) with the insertion loss varying between 2.3–4.5 dB over this range. The return loss was better than 10 dB.

Although the results of Table II and for the twin ferrite isolator structures indicate that the use of dielectrically-matched ferrites compared to tapered ferrites produced better performance, it would be desirable to improve the performance of the isolator incorporating tapered ferrites as there are obvious physical problems in attaching small dielectric pieces onto the ends of the rectangular ferrite slabs. It is hoped to achieve this by optimizing the taper length of the ferrites and also investigating the effects of different taper profiles.

C. Twin Ferrite Arrangement (Unidirectional Field)

An alternative arrangement of the twin ferrite coupled-slot finline isolator is shown in Fig. 8. Here it is shown from above a plan view of the finline circuit with the ferrites placed on opposite sides of the conductor surface. Thus, one section constitutes a double-layer structure and the other a sandwich structure. A length of resistive card is positioned over the lower slot in the region between the ferrites.

From the signal difference curves of Fig. 4(a) and (b), it was shown that the field displacement effect is reversed

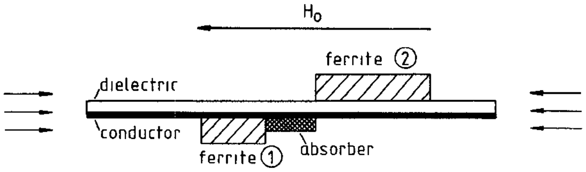

Fig. 8. Plan view of finline circuit with one ferrite slab placed on each side of the conductor and a mid-section of resistive card.

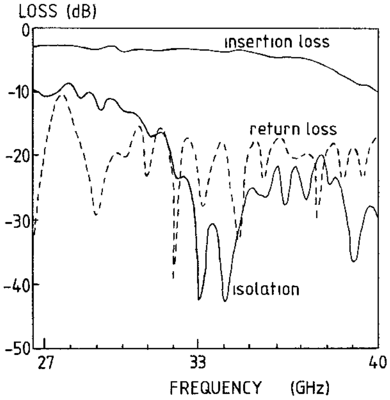

Fig. 9. Performance of the finline isolator with tapered ferrites placed on opposite sides of the finline circuit. $W=S=0.5$ mm; ferrite ①: $20\times3\times0.5$ mm^3, ferrite ②: $25\times3\times0.5$ mm^3, $H_0=160$ A/cm.

when the ferrite is moved from one side of the finline plane to the other. If the twin ferrite arrangement of Fig. 8 is magnetized by a single unidirectional magnetic field as shown, with the resistive card placed over slot ①; then, for propagation from the left-hand side into the sandwich-layer structure, the field will be perturbed into the lower slot (slot ① in Fig. 4(a)) and be absorbed. For propagation from the right-hand side into the double-layer structure, the field will be perturbed into the upper slot (slot ① in Fig. 4(b) if looking at the structure with the ferrite placed to the left of the finline) and, hence, away from the resistive card. Alternatively, isolation may be produced by reversing the applied magnetic field.

Because weaker nonreciprocity resulted when the ferrite was placed on the dielectric substrate side as was shown in Fig. 4(b) it was found that a longer ferrite slab was required to improve the nonreciprocity. Preliminary results of insertion loss, return loss, and isolation for this structure are shown in Fig. 9. A maximum isolation of 43.5 dB is observed with isolation greater than 20 dB, insertion loss less than 4.5 dB, and return loss better than 17 dB obtained over a bandwidth of 32–37 GHz (14.5 percent). However, greater than 20-dB isolation is retained over a bandwidth of 32–40 GHz (22.2 percent), but the insertion loss is prohibitively high at the higher frequencies.

V. Four-Port Circulator

Investigations have also been carried out on a nonreciprocal four-port finline coupler [7]. In the unmagnetized isotropic ferrite-loaded finline coupler, both odd and even modes propagate. With a longitudinally-magnetized ferrite slab placed on the coupled-slot section (Fig. 10), nonreciprocal coupling occurs, i.e., circulation. The circulator

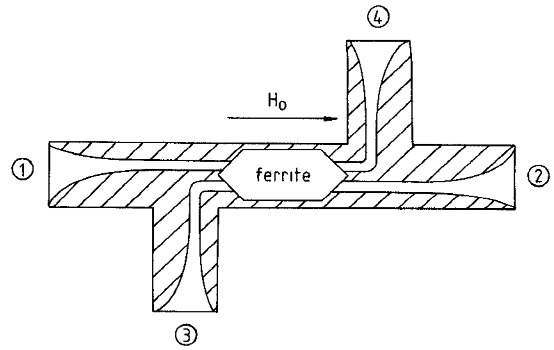

Fig. 10. Ferrite-loaded four-port finline coupler.

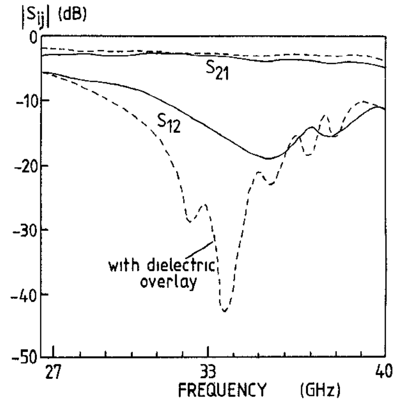

Fig. 11. Nonreciprocal coupling characteristics of ferrite-loaded four-port finline coupler with and without dielectric overlay placed on top of ferrite slab. $W=0.2$ mm, $S=1.0$ mm; ferrite: 30 mm long with 10 mm long tapers; dielectric overlay: $18\times3\times2$ mm^3, permittivity = 3.0, length of coupled-slot section = 35 mm, $H_0=160$ A/cm.

characteristics are shown in Fig. 11, where it is also shown that the nonreciprocal isolation (S_{12}) is improved by placing a dielectric overlay on top of the ferrite slab. This has the effect of concentrating the field within the ferrite slab [8], [9]. S-parameter curves of the nonreciprocal coupler are shown in Fig. 12(a) and (b) where four-port circulator behavior is clearly evident. Fig. 12(a) shows that a 20-dB isolation bandwidth of 3.6 GHz was produced at the coupling ports (S_{12}, S_{34}) with between 2.5–3.5-dB losses produced at the transmission ports (S_{14}, S_{32}). The return loss (S_{11}) was measured to be better than 15 dB. As shown in Fig. 12(b), the direction of circulation is reversed by reversing the applied field, as expected, but the isolation exhibits broad-band behavior, albeit at only approximately 15 dB.

It has been found from investigations on a ferrite-loaded coupled-slot finline where only the even mode propagates that for longitudinal magnetization there were no appreciable field displacement effects as has been demonstrated for the odd mode propagating only. Work is in hand to predict the odd-mode nonreciprocal propagation constants required to produce the conditions for nonreciprocal coupling. It is of interest to note that the selective behavior of two different modes has been discussed by John and Böck [10] in connection with a completely different structure, i.e., a microstrip-slot coupler.

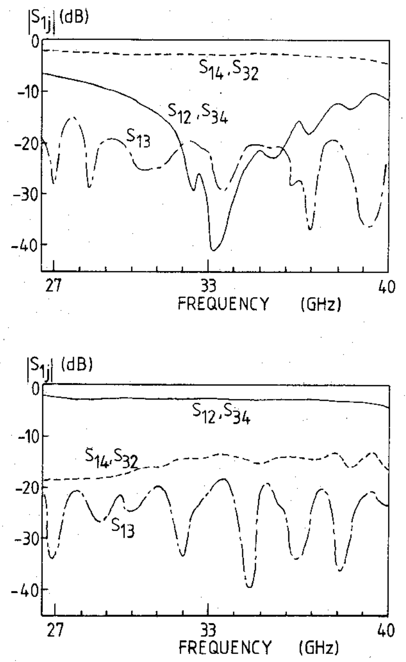

Fig. 12. Nonreciprocal transmission and coupling characteristics. Fig. 12(b) obtained by reversing H_0. Finline coupler parameters are as given in Fig. 11.

VI. Operation Above 40 GHz

These nonreciprocal coupled-slot finline configurations have a number of features that will be useful at frequencies above 40 GHz.These are

a) the closer mechanical tolerances are associated with the finline circuit (where they are more easily controlled) rather than with the ferrite slab,
b) the ferrite slab is several wavelengths long which makes grinding and handling easier,
c) the applied field is low despite the high frequency,
d) the need for hexagonal materials is less urgent,
e) broad-bandwidths appear to be possible.

VII. Conclusions

Isolator and circulator behavior have been demonstrated with coupled-slot finline structures loaded with ferrite slabs magnetized parallel to the direction of propagation. The isolator structures consist of a single slab ferrite-loaded line and twin slab ferrite-loaded lines with anti-parallel and unidirectional applied magnetic fields. It has been shown that, in the frequency range 26.5–40 GHz, reasonable isolation is achieved with very low values of applied magnetic field. The results have implications for similar components at higher frequencies. Theoretical and experimental work is in hand to improve these promising devices.

Acknowledgment

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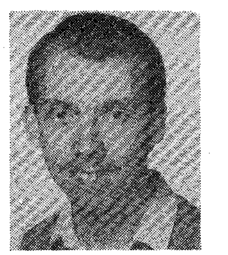
Lionel E. Davis (SM'65) received the B.Sc. and Ph.D. degrees from the University of Nottingham and the University of London, in 1956 and 1960, respectively. From 1959 to 1964, he was with Mullard Research Laboratories, Redhill, England, and, from 1964 to 1972, he was an Assistant and then Associate Professor of Electrical Engineering at Rice University, Houston, TX. In 1972, he joined Paisley College, Scotland, as Head of the Department of Electrical and Electronic Engineering, where he is now also Dean of Engineering. His current research interests are in millimetric-wave components and liquid crystal electrooptical switching for optical image processing.

Dr. Davis has served on the Council and other committees of the Institution of Electrical Engineers and several committees of the Science and Engineering Research Council. He has been a Visiting Professor at University College London (1970/71) and University of California San Diego (1978/79), and a Consultant for Bendix Research Laboratories (1966-68). He was a founding member of the Houston Chapter of the MTT-S.



David B. Sillars (M'83) was born in Irvine, Ayrshire, Scotland, on August 22, 1960. He received the B.Sc. (Hons.) degree in electrical and electronic engineering from Paisley College of Technology, Scotland, in 1982, where he has recently completed the Ph.D. degree in the area of millimeter-wave nonreciprocal components.

At present, he is employed as an SERC Research Assistant in the Department of Electrical and Electronic Engineering, Paisley College of Technology.