EDGE GUIDED WAVES FIVE YEARS LATER

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Abstract

This paper reviews the work made on edge guided waves (EGW) in the past five years. It is not comprehensive of all the results existing in the published literature, rather it concentrates on such selected topics as the radius of curvature of the guiding edge, magnetic, dielectric and ohmic losses, fringing field effects, inhomogeneous magnetic bias, and dielectric loading of the guiding edge. Performance data of some EGW isolators and circulators are also discussed.

Introduction

In May 1971 M. Hines published a paper on edge guided waves (EGW) in ferrite MIC's and strip-line circuits [1]. Since then a number of people have devoted their efforts to gain a better physical insight of the EGW phenomenon and to improve the performance of EGW devices. Today the knowledge of the physics underlieing EGW propagation in various geometries is at a fairly satisfactory stage even though the theory is only available for very simple models. Practical EGW devices in part fell short of the original expectations but they are now offering improved performance mainly in connection with large bandwidths and low insertion losses. The purpouse of the present paper is to illustrate the most significant improvements achieved in the past five years in EGW research.

EGW theory

Since 1971, Hines' analysis has been either improved or extended to include the following points: i) Radius of curvature of the guiding edge. ii) Magnetic, dielectric and ohmic losses. iii) Fringing field effects at the guiding edge. iv) Spatial inhomogeneity of the applied magnetic bias. v) Dielectric loading of the guiding edge. These topics will be dealt with extensively in the oral presentation of the paper. Here, due to space limitations, we just highlight the principal results in each area.

i) Radius of curvature of the guiding edge.
EGW behave differently depending upon the algebraic sign of the radius of curvature of the guiding edge [2]. In a semi-infinite strip conductor with a concave profile, r.f energy leaks from the EGW whenever the effective magnetic permeability μ_{eff} of the ferrite substrate is positive. In a finite geometry such as that of a practical EGW circulator the leaking field is quantized and manifests itself under the form of discrete ferrite volume (FV) modes. The suppression of these modes is one of the most difficult problems encountered in the construction of practical EGW devices. In the case of a strip conductor with a convex profile such as that of a MIC disk resonator of large radius, EGW may propagate unattenuated for both $\mu_{eff} > 0$ and $\mu_{eff} < 0$ in very much the same way as in a rectilinear geometry. More specifically, if perfect magnetic wall boundary conditions are used one finds that all the modes with a given azimuthal dependence, say $\exp(-jn\theta)$, are EGW in character, whilst those with a dependence $\exp(jn\theta)$ are of the FV type. Introduction of fringing field effects into the anlysis, however, corrects these results and indicates that even the fields with an $\exp(-jn\theta)$ dependence may be of the FV type for sufficiently high frequencies.

ii) Magnetic, dielectric and ohmic losses.
Dissipative effects may be introduced into the analysis of the EGW propagation in a formal manner by replacing the lossless values of the ferrite's constitutive parameters by complex quantities and charactenizing the metal conductors by a finite conductivity [3,4]. This type of analysis provides a quantitative evaluation of the specific attenuation suffered by EGW propagating along rectilinear guiding edges. Typically [4] it is found that an attenuation of 0.03 dB/cm. is to be expected in a semi-infinite microstrip deposited on a YIG + Al substrate of thickness 0.2 cm. in the frequency range 4 - 12 GHz.

iii) Fringing field effects.
The effect of fringing fields was originally studied by M. Hines [1] and identified with an upper cut off frequency for the EGW propagation. Hines' model has been recently [5] improved by means of a semi-empirical analysis. In this analysis the fringing fields are characterized by a fringing field parameter b/b' which is related to the fringing field transversal admittance Y_f via the relation

$$Y_f = -j \frac{L}{b} \frac{b}{b'} \left(n_y^2 - 1\right)^{1/2}$$

Here Y_0 is the characteristic admittance of vacuum, L/b is the ratio between the guiding edge's length and substrate thickness, n_y is the refractive index in the direction of propagation. For many cases of practical interest it is found that $0.4 < b/b' < 0.7$. For a rectilinear geometry the upper cut off frequency as a function of b/b' is defined by the implicit relation

$$\frac{\mu_2}{\mu_1} = -\frac{b}{b'} \mu_{eff} \left(1 - \frac{1}{\epsilon_f \mu_{eff}}\right)^{1/2}$$

where μ_1 and μ_2 are the diagonal and off-diagonal entries of the magnetic permeability tensor and ε_f is the relative dielectric permettivity of the ferrite. A similar relation exists for the upper cut-off frequency in a disk geometry.

iv) Inhomogeneous magnetic bias.

A non dissipative technique for suppressing FV modes resonating in EGW structures with concave guiding edges, makes use of an inhomogeneous magnetic bias [6,7]. The inhomogeneity must guarantee that $\mu_{eff} < 0$ at some point under the strip conductor. Preliminary theoretical investigations [8] exist only for rectilinear microstrip immersed in a magnetic bias with a linear variation in the crossection. More specifically the bias has a maximum on the microstrip axis and decreases linearly toward the edges of the strip conductor. The most interesting result obtained so far, is that a tranversal field displacement effect exists as long as $\mu_{eff} < 0$ on the axis of the structure. This phenomenon can in fact be identified with a sort of "generalized" EGW wherein the r.f. field components have a transversal distribution which is oscillatory in the vicinity of the edge and decays exponentially in the central part of the structure.

v) Dielectric loading of the guiding edge.

In its original work M. Hines presented a method for suppressing the cut off effect due to the fringing fields. Such a method used a dielectric loading of the guiding edge to compensate for the inductive tranversal susceptance of the fringing fields. As an example, a capacitive susceptance of 1.25 pF/cm. was used in a semi-infinite microstrip on a YIG substrate 0.025 inch thick. To gain a better physical insight of the compensation effects introduced by the dielectric loading, a field analysis has been carried out for a rectilinear geometry [9]. By plotting the transversal distributions of the field components it has been found that the dielectric in fact produces a considerable amount of transversal field displacement at frequencies higher than upper cut off frequency. At very high frequencies however reciprocal dielectric concentration effects become dominant and non-reciprocal effects cease to exist. Very useful indications can be obtained from this type of analysis on the dielectric constant and thickness of the dielectric slab which would optimize the performance of an EGW isolator.

EGW devices.

Isolators. The original Hines' isolator had the characteristics shown in the first row of Table I. In this Table the columns respectively indicate the operation bandwidth, insertion loss, isolation, saturation magnetization, and applied magnetic bias. Since 1971 a number of EGW isolators have been built operating in various frequency bands. In Table I we have reported the data relative to some laboratory prototypes as well as some commercial devices (last two rows). Notice how the applications of EGW isolators have been extended to frequencies as low as 0.2 GHz. and as high as 18 GHz. in some cases with two-octave bandwidths. Recently, however, the attention has shifted from one-dB-insertion loss, two-octave isolators to 0.4 dB insertion loss, one-octave isolators. The difficulties encountered in the realization of these isolators can be appreciated by recognizing that the following conflicting conditions must be met: i) gradual taper sections, ii) short guiding edges, iii) large transversal dimensions) iv) small overall dimensions. Furthermore, in EGW isolators with an external load the additional condition must be satisfied that the load be matched to the EGW travelling in the forbidden direction. This means that its physical and geometrical characteristics must be carefully chosen. Unfortunately such a choice is in general made on an empirical basis due to the complete lack of theoretical predictions. In ref. 4 the authors report on a load material with a dielectric constant $(30 - j3)\ \varepsilon_o$ and a magnetic permeability $(4-j)\mu_o$ used in a YIG+Al stripline isolator operating in the 4-10 GHz. frequency range. As far as the optimal shape of the load is concerned no information as yet exists in the published literature. Another problem to be solved in the construction of a stripline EGW isolator is the realization of suitable low-loss, broadband coax to stripline transitions. Also in this case cut and try techniques are in general applied. Finally it is worth mentioning the realization of EGW isolators [10] wherein the dissipative effect of the external load is replaced by the magnetic losses associated with a short circuited strip conductor's edge.

Circulators. Unsymmetrical multiport circulators as well as three-port and four-port symmetrical circulators have been constructed. Here we shall concentrate on the symmetrical structures as they received greater attention. The design criteria for these devices are the same as those adopted for the isolators. Obviously in the circulators there must to be no dissipative material and, consequently, the role plaied by the load in suppressing the ferrite volume modes must now be performed by some other means. As previously anticipated the use of an inhomogeneous magnetic bias has proven very efficient in suppressing the unwanted modes [6,7]. Experimental evidence exists that this suppression mechanism is basically different from the usual inhomogeneous broadbanding [6]. Three port symmetrical MIC circulators [6] have been built with a max. insertion loss of 0.8 dB. and an average isolation of 30 dB. over the band 8.4 - 12.4 GHz. The inhomogeneous magnetic bias had a maximum of 3.75 KOe at the center of the circulator and a minimum of 3.15 KOe. at the substrate edge. The optimum shape of the strip conductor was obtained by cut and try techniques. Four port symmetrical MIC circulators were also constructed having a star shaped strip conductor with either parabolic or hyperbolic profiles [7]. The best X-band results were obtained in a circulator with a shield diameter of 13 mm. an outer diameter of 30 mm. and a magnetic bias which varied from a max. of 4.5 KOe to a min. of 1.5 KOe. The insertion loss ranged from .4 to .8 dB. and the isolation was always greater than than 20 dB.

Conclusions

In this paper we have presented some of the progress made in the field of edge guided waves in the past five years. Even though the practical realization of EGW devices has fallen short of the original expectations, the field still possesses considerable vitality. In the light of the results so far obtained we may anticipate that in a near future EGW isolators with a very low insertion loss, high isolation and large operation bandwidth will enjoy the increasing favour of microwave system designers. On the other hand, EGW circulators will not succeed in becoming competitive to other more traditional solutions due to their size and complexity of construction. Future trends in EGW research may include such topics as a modal solution of EGW structures with concave profiles, new techniques for broadband transfer of EGW energy into an adjacent dissipative load, study of the relation ship among "wall affected mode" [11], EGW mode and Y-junction MIC circulators.

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- TABLE I -

	ΔF GHz	I.L. dB	Is. dB	$4\pi M_s$ KOe	H_o Koe
HINES	6-12	~ 1	> 20	1.78	1.9
BLANC et al.	5-12	< 1	> 20	1.78	1.76
COURTOIS et al.	3.5 - 14.5	< 1	> 20	1.78	-
COURTOIS et al.	0.2 - 0.4	< 3	> 18	1.78	2
LEMKE	12 - 18	~1.5	> 37	1.78	4.75
Comm. Type	2 - 7	< 1	> 15	-	-
Comm. Type	3.5 - 11	< .9	> 20	-	-