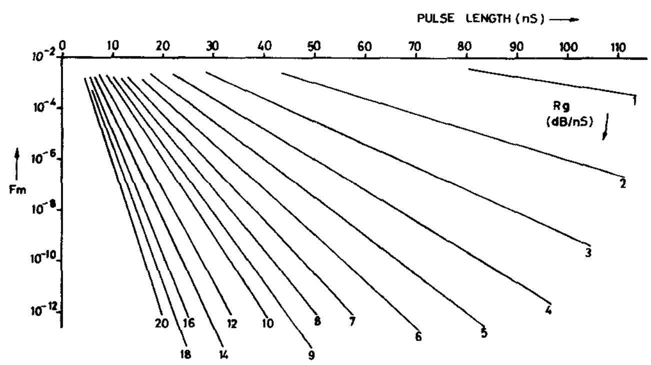


Fig. 12. Probability (F_m) of a missed pulse versus pulselength.

any significant mean level from the *Ku*-band noise channel implies that, in this case, moding was not making a significant contribution to the mean inter-spectral noise level.

Front Edge Jitter and Missed Pulses

From the jitter distributions shown in Fig. 8, it can be seen that the probability of a late pulse decreases rapidly with time. However, occasionally a pulse will be late by 30 percent or more of the mean pulse duration and this would register as a missing pulse as defined in the introduction. Integration of (1) above shows that the probability $F(t)$ that a pulse will reach the reference level after time t asymptotically becomes,

$$\log_{10} F(t) = -\frac{(t-T_D)}{10} \cdot R_g$$

where R_g, the RF growth rate, is given by

$$R_g = \frac{4.34}{\tau} \text{dB/ns}$$

and T_D, the dealy time, is given by

$$\exp \frac{T_D}{\tau} = \frac{P_{\text{ref}}}{P_{\text{mean}}}.$$

Physically T_D is the time required for the most probable power growth curve to reach the reference level.

Now, assuming the mean starting time is equal to T_D, a missed pulse will occur when

$$t - T_D \geqslant 0.3\, T_p$$

where T_p is the pulselength, so the probability of a missed pulse, caused by front edge jitter only, is given by

$$\log_{10} F_m \simeq -0.03 \cdot R_g \cdot T_p. \tag{2}$$

Plots of F_m versus T_p, for different R_g, are shown in Fig. 12, and it can be seen that the probability of jitter causing a missed pulse decreases very rapidly with increasing pulselength and RF growth rate. Note the missed pulse rate is given by F_m multiplied by the PRF.

It is interesting to note from the above that digital measurement of the missing pulse count on short pulse conventional modulators gives information about the rate of RF growth of the magnetron.

Conclusions

Front edge jitter is a major source of mean inter-spectral noise, it is fundamental to the starting of a magnetron and depends on the rate of RF growth only. For very rapid rate of rise of the modulation pulse, jitter may be anomalously low.

In the increasingly more common case of very short pulses, or when the RF growth rate is very low, front edge jitter can result in "traditional" missing pulses ($\leqslant$70-percent mean energy).

Transient increases in the inter-line noise (spikes) can be caused by the magnetron operating in the wrong mode.

Specifications calling up low levels of mean inter-line noise imply small front edge jitter and, therefore, virtually no missing pulses.

In a system in which front edge jitter is the only source of instability, a measurement of the missing pulse count could, together with (2), be used to calculate the rate of RF growth.

References

[1] B. Vyse, "Jitter and the growth of RF oscillation in pulsed magnetrons," Ph.D. dissertation, Edinburgh, 1971.
[2] B. Vyse and M. A. Hulley, "Growth processes and inter-line noise in pulsed magnetrons," in *Proc. 7th Int. Conf. Microwave and Optical Generation and Amplification*, Hamburg, 1968.
[3] M. A. Hulley and B. Vyse, "A mathematical model of RF build-up and inter-line noise in pulsed magnetrons," in *Proc. 8th Int. Conf. on Microwave and Optical Generation and Amplication*, Holland, 1970.
[4] G. G. Macfarlane, "On the energy spectrum of an almost periodic succession of pulses," *Proc. IRE*, vol. 30, p. 1139, 1949.
[5] M. A. Hulley and B. Vyse, "The investigation of pulsed magnetron performance at *X*-band with voltage rise times in the nanosecond region," in *Proc. 6th Int. Conf. Microwave and Optical Generation and Amplification*, Cambridge, 1966.
[6] S. O. Rice, "Mathematical analysis of random noise," *Bell Syst. Tech. J.*, vol. 24, part III, p. 100, 1945.

Guided Magnetostatic Waves of the YIG Plate Magnetized Nonuniformly

KEN' ICHIRO YASHIRO AND SUMIO OHKAWA

***Abstract*—It is shown that magnetostatic waves may propagate along a discontinuity of the internal dc magnetic field when its strength is made nonuniform such as a step. Backward waves may also propagate in this magnetic field configuration.**

In the past, the effects of nonuniformity of the internal dc magnetic field on the generation or propagation characteristics of magnetostatic modes have been discussed by a number of investigators [1]–[6]. Recently, it has been reported [7] that controlled magnetostatic waves can propagate in desired frequency ranges at desired speed if appropriate dc magnetic field gradients are applied. In this work, we study magnetostatic wave propagation for the case in which the dc magnetic field in the inner region of the sample is stronger or weaker than the field in the outer region.

The external static field shall be applied by using pole pieces such that the internal magnetic field is deliberately nonuniform. Then, which modes may propagate in the structure shown in Fig.

Manuscript received October 28, 1980; revised January 29, 1981.
The authors are with the Department of Electronic Engineering, Faculty of Engineering, Chiba University, Chiba, 260 Japan.

0018-9480/81/0700-0745$00.75 ©1981 IEEE

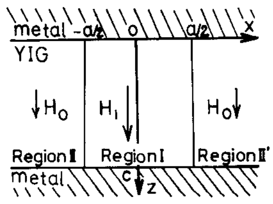


Fig. 1. Cross-sectional view of the guide geometry.

1? The magnetic static field intensity in the region I, H_i, is different from that in the region II, H_o, although both fields are uniform along the y axis. Two surfaces ($z=0, c$) are metalized and the biasing field is z-directed. This mathematical model is not a realistic representation of the physical configuration, but is chosen for the sake of mathematical simplicity. The magnetostatic approximation is employed. The magnetostatic potential has the form $\phi(x,z)\exp[j(\omega t - k_y y)]$, and satisfies the following equations:

$$\mu_i\left(\frac{\partial^2\phi_i}{\partial x^2} - k_y^2\phi_i\right) + \frac{\partial^2\phi_i}{\partial z^2} = 0$$

$$\boldsymbol{h}_i = \nabla\phi_i, \quad \boldsymbol{b}_i = \mu_0\begin{pmatrix} \mu_i & j\kappa_i & 0 \\ -j\kappa_i & \mu_i & 0 \\ 0 & 0 & \mu_z \end{pmatrix}\boldsymbol{h}_i, \qquad i=\text{I},\text{II} \tag{1}$$

where the indexes I, II correspond to the region I and the region II, II′, respectively. The normal component of the magnetic induction must vanish on the metal, that is, $b_z=0$ at $z=0$, c. Hence ϕ_i is proportional to $\cos\left(\frac{n\pi}{c}z\right)$ ($n=0,1,2,\cdots$). Consequently the magnetic potential may be written as follows:

$$\phi_{\text{I}} = (Ae^{-\alpha_I x} + Be^{\alpha_I x})\cos\frac{n\pi}{c}z e^{-jk_y y}$$

$$\phi_{\text{II}} = Ce^{\alpha_{\text{II}} x}\cos\frac{n\pi}{c}z e^{-jk_y y}$$

$$\phi_{\text{II}'} = De^{-\alpha_{\text{II}} x}\cos\frac{n\pi}{c}z e^{-jk_y Y} \tag{2}$$

with

$$\alpha_{\text{I,II}} = \sqrt{k_y^2 + (n\pi/c)^2/\mu_{\text{I,II}}}\,.$$

By considering the continuity of h_z, h_y, and b_x at the interfaces at $x=\pm a/2$, the following equation is obtained in order that a nontrivial solution may exist:

$$e^{2\alpha_{\text{I}} a} = \frac{(\alpha_{\text{I}}\mu_{\text{I}} - \alpha_{\text{II}}\mu_{\text{II}})^2 - (\kappa_{\text{I}} - \kappa_{\text{II}})^2 k_y^2}{(\alpha_{\text{I}}\mu_{\text{I}} + \alpha_{\text{II}}\mu_{\text{II}})^2 - (\kappa_{\text{I}} - \kappa_{\text{II}})^2 k_y^2}. \tag{3}$$

This equation has also a solution when α_{I} is pure imaginary, that is, μ_{I} is negative. Putting $\alpha_{\text{I}} = -j\alpha'_{\text{I}}$, (3) may be rewritten as

$$\tan\alpha'_{\text{I}} a = \frac{2\alpha'_{\text{I}}\alpha_{\text{II}}\mu_{\text{I}}\mu_{\text{II}}}{(\alpha'_{\text{I}}\mu_{\text{I}})^2 - (\alpha_{\text{II}}\mu_{\text{II}})^2 + (\kappa_{\text{I}} - \kappa_{\text{II}})^2 k_y^2}. \tag{4}$$

When μ_{I} is positive, the magnetostatic waves decay exponentially away from the interface between the regions I and II, or the regions I and II′. The modes are considered surface waves. When μ_{I} is negative, the waves will propagate as the volume modes.

Here (3) will be examined in detail when the α_{I} becomes real (surface wave case). The following numerical values are used for the computation: the width of the region I, $a=5$ mm, the thickness of the YIG plate, $c=0.7$ mm, the saturation magnetization, $4\pi M=1760$ G, and the gyromagnetic ratio, $\gamma=2.8$ MHz/Oe. The magnetization curve is approximated by the piecewise linear representation such that the magnetization increases linearly from zero to the saturation if the internal dc field is less than 2 Oe and otherwise it is constant at the saturation magnetization. For the saturated ferrite, Polder tensor permeability is used. However, the off-diagonal elements of the tensor permeability for partially magnetized ferrites are taken from [8].

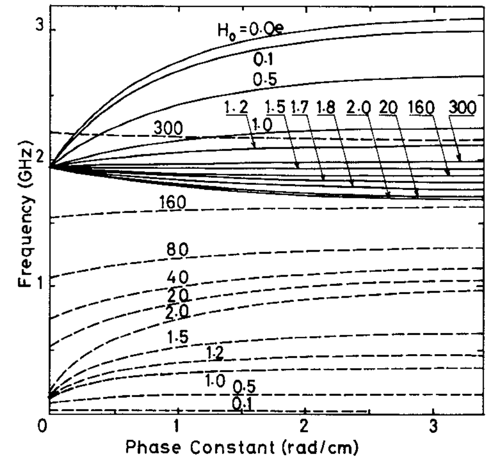


Fig. 2. Dispersion relations for the z independent magnetostatic waves ((3) with $n=0$) in the configuration shown in Fig. 1. H_i is assumed to be 240 Oe.

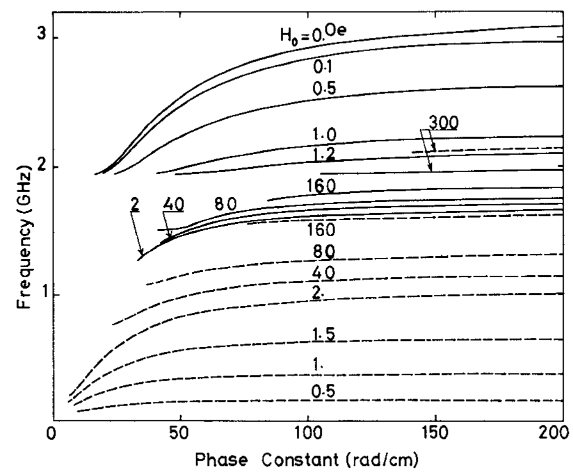


Fig. 3. Dispersion relations for the z dependent magnetostatic waves ((3) with $n=1$) in the configuration shown in Fig. 1. H_i is assumed to be 240 Oe.

The results are shown in Figs. 2 and 3. It is assumed that $H_i = 240$ Oe. Fig. 2 shows the dispersion relations of $n=0$ magnetostatic modes, of which amplitudes are independent of z. There exist two groups. It can be seen from full lines of Fig. 2 that one exists even though $H_o=0$ Oe. It becomes a backward wave as H_o is close to H_i. The other, which is indicated by a broken line, exists only if the outer region is magnetized. The smaller the difference between H_i and H_o becomes, the narrower the magnetostatic wave bandwidth is confined. As expected, if H_o is equal to H_i, there is no guided wave. When H_o is stronger than H_i, the magnetostatic waves can propagate again and the latter group becomes in turn a backward wave. In multilayered structures containing YIG films of different $4\pi M$, forward and backward surface wave solutions were also found [9].

The dispersion relations of the waves, which have an amplitude variation in the z-direction ($n=1$), are shown in Fig. 3. Since exp $(2\alpha_{\text{I}} a)$ in (3) is much greater than unity with the assumed dimensions, the propagation constants of the waves of which $n \geq 2$, are obtained from the results in Fig. 3 by multiplying n. It is seen that the z dependent waves have the similar properties except that they are always forward waves.

We conclude that the nonuniformity of the dc magnetic field is available for magnetostatic waveguides. The possibility of the z independent backward magnetostatic waves is also sugessted.

REFERENCES

[1] E. Schlomann and R. I. Joseph, "Theory of spin-wave generation in nonuniform magnetic fields," *Proc. IEEE*, vol. 51, pp. 1269–1270, Sept. 1963.

[2] E. Schlomann, "Generation of spin waves in nonuniform magnetic fields. I. Conversion of electromagnetic power into spin-wave power and vice versa," *J. Appl. Phys.*, vol. 35, pp. 159–166, Jan. 1964.

[3] R. W. Damon and H. Van de Vaart, "Dispersion of spin waves and magnetoelastic waves in YIG," *Proc. IEEE*, vol. 53, pp. 348–354, Apr. 1965.

[4] E. Schlomann, R. I. Joseph, and T. Kohane, "Generation of spin waves in nonuniform magnetic fields, with application to magnetic delay lines," *Proc. IEEE*, vol. 53, pp. 1495–1507, Oct. 1965.

[5] J. D. Adam, "Delay of magnetostatic surface waves in Y.I.G.," *Electron. Lett.*, vol. 6, pp. 718–720, Oct. 1970.

[6] M. Bini, L. Millanta and N. Rubino, "Gaussian-beam distribution of magnetostatic surface waves in inhomogeneous dc field," *J. Appl. Phys.*, vol. 46, pp. 3175–3177, July 1975.

[7] F. R. Morgenthaler, "Bound magnetostatic waves controlled by field gradients in YIG single crystals and epitaxial films," *IEEE Trans. Mag.*, vol. MAG-14, pp. 806–810, Sept. 1978.

[8] D. J. Masse and R. A. Pucel, "Microstrip propagation on magnetic substrate—Part II: Experiment," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 309–313, May 1972.

[9] T. Wolfram, "Magnetostatic surface waves in layered magnetic structures," *J. Appl. Phys.*, vol. 41, pp. 4748–4749, Oct. 1970.

Contributors

Takeo Abe (M'79) was born in Niigata, Japan, on March 8, 1926. He received the B.Eng. and D.Eng. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1949 and 1966, respectively.

From 1950 to 1959, he was a Research Scientist at the Electrotechnical Laboratory, Tokyo Japan. From 1962 to 1966 he was an Associate Professor of Electrical Engineering at Tokyo Institute of Technology. From 1966 to 1978, he was a Professor of Electronic Engineering at Niigata University. Since 1978, he has been a Professor of Information Engineering at Niigata University, Niigata, Japan. He is engaged in research and education in electromagnetic theory and microwave engineering.

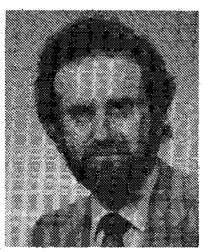
Dr. Abe is a member of the Institute of Electronics and Communication Engineers of Japan and the Japanese Society of Snow and Ice.

Mohamad D. Abouzahra (S'79) was born in Beirut, Lebanon, on June 15, 1953. He received the B.Sc. degree with distinction in electronics and communications from the Department of Electrical Engineering, Cairo University, Cairo, Egypt, in 1976, and the M.Sc. degree in electrical engineering from the University of Colorado, Boulder, in 1978.

From 1976 to 1977 he was with the Ministry of Education in Kuwait. At present he is a Ph.D. Candidate and a Research Assistant at the University of Colorado. His current fields of interest include microstrips, wide-band dielectric directional couplers, and the dielectric image line.

Michael Alberty was born in Coesfeld, West Germany, on May 9, 1952. He received the Dipl.-Ing. degree in electrical engineering from the Technische Universität Karlsruhe, Karlsruhe, West Germany, in 1976.

Since then he has been with AEG-Telefunken, Backnang, West Germany, where he has worked on parametric amplifiers and low-noise FET amplifiers. He is now engaged in the development of microwave modulators and demodulators for regenerative satellite repeaters.



John W. Bandler (S'66–M'66–SM'74–F'78) was born in Jerusalem, Palestine, on November 9, 1941. He studied at Imperial College of Science and Technology, London, England, from 1960–1966. He received the B.Sc. (Eng.), Ph.D., and D. Sc. (Eng.) degrees from the University of London, London, England, in 1963, 1967, and 1976, respectively.

He joined Mullard Research Laboratories, Redhill, Surrey, England, in 1966. From 1967 to 1969 he was a Postdoctorate Fellow and Sessional Lecturer at the University of Manitoba, Winnipeg, Man., Canada. He joined the Department of Electrical Engineering, McMaster University, Hamilton, Ont., Canada, as Assistant Professor in 1969. He became Professor in 1974, Chairman of the Department in 1978, and Dean of the Faculty of Engineering in 1979. He has been Coordinator of the Research Group on Simulation, Optimization and Control since 1973. During part