

AD-769 132

EFFICIENT MODE CONVERSION IN $Gd(.5)Y(2.5)$
Ga, IRON GARNET THIN FILM WAVEGUIDES

Samuel C. Tseng, et al

IBM Thomas J. Watson Research Center

Prepared for:

Office of Naval Research
Advanced Research Projects Agency

September 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

EFFICIENT MODE CONVERSION IN $Gd_{0.5}Y_{2.5}Ga$, IRON GARNET THIN FILM WAVEGUIDES

2nd Quarterly Technical Report
(15 April 1973 - 15 July 1973)

September, 1973

by

A. R. Reisinger
S. C. Tseng (principal investigator)

Prepared under Contract N00014-73-C-0256

Sponsored by

Advanced Research Projects Agency

ARPA Order No. 2327
Program Code No. 6514
Amount - \$99,000

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

by

IBM Corporation
Thomas J. Watson Research Center
P. O. Box 218
Yorktown Heights, New York 10598

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

AD 769132

TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	1
II. THEORETICAL ANALYSIS	2
III. EXPERIMENTAL RESULTS	5
3.1 Electrical Serpentine Circuit	5
3.2 Periodic Permalloy Structure	8
IV. CONCLUSIONS	
V. FINANCIAL STATEMENT	10
APPENDIX	12

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

IBM Thomas J. Watson Research Center
PO Box 218
Yorktown Heights, New York 10598

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE

Efficient Mode Conversion in $Gd_{0.5}Y_{2.5}Ga_1$ Iron Garnet Thin Film Waveguides

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Tseng, Samuel C.; Reisinger, Axel R.; Powell, Carl G.
(S. C. Tseng, Principal Investigator)

6. REPORT DATE

September, 1973

7a. TOTAL NO. OF PAGES

24 40

7b. NO. OF REFS

9

8a. CONTRACT OR GRANT NO.

N00014-73-C-0256

9a. ORIGINATOR'S REPORT NUMBER(S)

b. PROJECT NO.

c.

d.

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release, distribution unlimited.

11. SUPPLEMENTARY NOTES

Details of illustrations in
this document may be better
studied on microfiche.

12. SPONSORING MILITARY ACTIVITY

Advanced Research Projects Agency
ARPA Order No. 2327

13. ABSTRACT

The implementation of periodic reversals of magnetization along the direction of propagation of light, at locations where TE and TM modes become 180° out of phase, is discussed. Two approaches have been followed: (i) the conventional electrical serpentine circuit and (ii) a novel periodic permalloy structure. Using these techniques, we have observed conversion efficiencies of 92% and 80%, respectively, in two $Gd_{0.5}Ga_1$ iron garnet thin film waveguides grown on GGG substrates. Experimental results are examined in the light of the theory of electromagnetic wave propagation through bulk crystals possessing both Faraday rotation and birefringence, adapted to the case of mode conversion in magneto-optic waveguides.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Magneto-optics Garnet Films Optical Waveguides Modulation Mode Conversion						

1. INTRODUCTION

During this reporting period, we have concentrated our efforts on increasing the mode conversion efficiency in our magneto-optic thin film waveguides by periodic reversals of the magnetization along the direction of propagation of light. We have implemented this principle following two different approaches: (i) using an electrical serpentine circuit, which was first introduced by Tien¹ and (ii) using a novel periodic permalloy structure.

Section II summarizes a theoretical analysis of mode conversion in bulk crystals exhibiting both Faraday rotation and birefringence, as worked out by Tabor and Chen², and extended to the case of periodic magnetization reversals. The theory is expected to be readily applicable to mode conversion in magneto-optic waveguides, where the intrinsic mismatch between TE and TM modes plays the role of an effective birefringence.

Our experimental results are discussed in Section III. The design of our electrical serpentine circuit, although crude, enabled us to verify Tabor's theoretical formulation and to observe a DC conversion efficiency of 92%.

The remainder of the section is devoted to the discussion of a novel method to implement periodic reversals of the magnetization, in which the magneto-optic waveguide is subjected to the field generated by a properly biased periodic permalloy structure. Using this technique, we have observed 80% conversion efficiency at the time of this writing.

II. THEORETICAL ANALYSIS

The problem of Faraday rotation in birefringent media has been studied in the case of bulk magneto-optic crystals described by the following dielectric tensor²:

$$||\epsilon|| = \begin{bmatrix} \epsilon_x & j\delta & 0 \\ -j\delta & \epsilon_y & 0 \\ 0 & 0 & \epsilon_z \end{bmatrix} \quad (1)$$

The off-diagonal element δ changes its sign upon reversal of the applied magnetic field H .

Electromagnetic wave propagation along the z -axis is written in the form of a matrix relation:

$$\begin{bmatrix} E_x(z_2) \\ E_y(z_2) \end{bmatrix} = T(z_2 - z_1) \begin{bmatrix} E_x(z_1) \\ E_y(z_1) \end{bmatrix} \quad (2)$$

T is a 2×2 transmission matrix which takes into account the birefringence and magneto-optic properties of the crystal:

$$T = \begin{bmatrix} \cos \phi/2 - j \cos \chi \sin \phi/2 & -\sin \chi \sin \phi/2 \\ \sin \chi \sin \phi/2 & \cos \phi/2 + j \cos \chi \sin \phi/2 \end{bmatrix} \quad (3)$$

where

$$\phi = \Delta\beta (z_2 - z_1) \quad (4a)$$

$$\Delta\beta \approx k_0 (\epsilon_x^{1/2} - \epsilon_y^{1/2}) \quad (4b)$$

$$\cos \chi = (1 - \alpha^2)/(1 + \alpha^2) \quad (4c)$$

$$\sin \chi = 2\alpha/(1 + \alpha^2) \quad (4d)$$

$$\alpha = 2\delta / \{ (\epsilon_x - \epsilon_y) - [(\epsilon_x - \epsilon_y)^2 + 4\delta^2]^{1/2} \} \quad (4e)$$

It follows that α , and therefore χ , change their sign upon reversal of the applied magnetic field.

The foregoing analysis can be expected to be directly applicable to the case of magneto-optic film waveguides, provided that electromagnetic fields be well confined within the film, i.e. that the guided modes of interest be sufficiently above cutoff. The mismatch $\Delta\beta$ is now defined as the difference in the propagation constants of TE and TM modes:

$$\Delta\beta = \beta_{TE} - \beta_{TM} \quad (5)$$

It is shown in the Appendix that this matrix formulation gives exactly the same result for the mode conversion efficiency R as that obtained from coupled mode theory:³

$$R(z) = (1 + B^2)^{-1/2} \sin[\gamma z (1 + B^2)^{1/2}] \quad (6)$$

where γ is the "coupling strength" or optical rotatory power and the coefficient B is defined by:

$$B = \Delta\beta / 2\gamma \quad (7)$$

Because of the intrinsic phase mismatch $\Delta\beta$ between TE and TM modes, the maximum conversion efficiency is limited to typically a few percent in magneto-optic waveguides. It is known that this limitation can be overcome by periodically reversing the magnetization along the light propagation path at locations where the phase difference ϕ between "free" and "forced" waves

reaches π (or a multiple thereof)¹. From Eq. (4a) we obtain:

$$\Delta z = (\Lambda/2) = \pi/\Delta\beta \quad (8)$$

The transmission matrix T in Eq. (2) will now be equal to a product of partial matrices:

$$T = \underbrace{T^+ \left(\frac{\Lambda}{2}\right) T^- \left(\frac{\Lambda}{2}\right)}_{\text{one period}} \underbrace{T^+ \left(\frac{\Lambda}{2}\right) T^- \left(\frac{\Lambda}{2}\right)}_{\text{one period}} \dots \quad (9)$$

where $T^+ (\Lambda/2)$ and $T^- (\Lambda/2)$ correspond to propagation over a half period $(\Lambda/2) = \pi/\Delta\beta$ for a longitudinal field in the positive and negative directions, respectively. Expressions for these matrices are obtained by setting $\phi = \pi$ in Eq. (3):

$$T^+ (\Lambda/2) = \begin{bmatrix} -j\cos\chi & -\sin\chi \\ \sin\chi & j\cos\chi \end{bmatrix} \text{ and } T^- (\Lambda/2) = \begin{bmatrix} -j\cos\chi & \sin\chi \\ -\sin\chi & j\cos\chi \end{bmatrix} \quad (10)$$

If magnetization reversals are repeated over m periods, matrix multiplication carried out m times in Eq. (9) gives a total transmission matrix $T^{(m)}$:

$$T^{(m)} = (-1)^m \begin{bmatrix} \cos 2m\chi & j \sin 2m\chi \\ j \sin 2m\chi & \cos 2m\chi \end{bmatrix} \quad (11)$$

If the wave is originally polarized in the x -direction (say TE mode with $E_y(0) = 0$), one obtains from Eqs. (2) and (11):

$$E_y(m\Lambda) = (-1)^m j \sin 2m\chi E_x(0) \quad (12)$$

The conversion efficiency can in principle reach 100% after a sufficient number of periodic field reversals.

III. EXPERIMENTAL RESULTS

We have implemented this principle of periodic reversal of magnetization, following two different approaches: 1) electrical serpentine circuit, and 2) a novel periodic permalloy structure.

III. 1. ELECTRICAL SERPENTINE CIRCUIT

Although this part of our investigation does not involve any fundamentally new idea, as it closely follows Tien's work, it enabled us to make certain interesting observations which will now be discussed. The circuit design which we used is schematically illustrated in Fig. 1. It consists basically of two screws of appropriate size and thread, mounted parallel to each other on a rigid aluminum frame, around which a solenoid wire is wound in an alternate fashion. The use of 2 screws of different pitch produces a circuit with variable periodicity. Electrical connections can easily be made in such a way that the number of periods activated can be changed. The magneto-optic film to be analyzed is gently pressed, face down, on the wire grid. The structure is easy to construct, proves to be a convenient testing tool, and works surprisingly well. Fig. 2 shows the modulated TE output after propagating in a $\text{Gd}_{0.5}\text{Ga}_{1.5}$ iron garnet film of thickness $8.4\text{ }\mu\text{m}$ on a GGG substrate, when an AC current of frequency $\Omega = 60\text{Hz}$ is fed into a circuit comprising 8 periods. Eighty-two per cent depletion was measured for a peak current of 1.3 amp. The periodicity Λ of the circuit was designed to fit an experimentally measured guided index mismatch $\Delta n_g \sim 1.15 \times 10^{-3}$ between the modes TE_5 and TM_5 :

$$\Lambda \cdot \Delta n_g = \lambda_0$$

(13)

where $\lambda_c = 1.15 \mu\text{m}$ is the free-space wavelength of the He-Ne laser radiation used in these experiments.

If the output is passed through an analyzer with azimuth θ relative to the original polarization direction, the intensity detected is given by:⁴

$$I_D \propto \cos^2 \theta - T_{12}^2 \cos 2\theta + (1/2) T_{12} (T_{11} + T_{11}^*) \sin 2\theta \quad (14)$$

where the T_{ij} 's are the matrix elements defined in Eq. (3). Eqs. (4) show that T_{12} contains the modulating frequencies Ω , 3Ω , 5Ω , etc., while T_{11} contains 0 , 2Ω , 4Ω , etc.

After isolating the various components of the photomultiplier output by means of an electronic filter, the Ω - and 2Ω terms are shown in Fig. 3 to vary as $\cos 2\theta$ and $\sin 2\theta$, respectively, in agreement with Eq. (14).

The B-H curve of the magneto-optic guide is shown in Fig. 4 for two orthogonal directions in the phase of the film. The direction of propagation of light was chosen to coincide with the easy axis. It is seen that saturation is achieved with an applied field H_s of about 1.5 Oe. With reference to Fig. 5, it can be argued that the onset of mode conversion will occur at a threshold current I_0 for which some portions of the film just underneath the wires experience a magnetic field at least equal to $H_s = 1.5$ Oe. As the current I increases, the unused portions of the film (shaded areas in Fig. 5) should decrease in size and the conversion efficiency is expected to go up. This is indeed what happens, as evidenced in Fig. 6. The DC conversion efficiency reached 92% for a current of 2 amps.

With the geometry indicated in Fig. 5, the longitudinal magnetic field directly under a wire can be written as:

$$H_L = \frac{I}{2\pi h} \left\{ 1 + 2 \sum_{m=1,2,3,\dots} (-1)^m [(m\Lambda/2h)^2 + 1]^{-1} \right\} \quad (15)$$

where h is the distance between center of wire and surface of the film. In Eq. (15), the influence of all neighboring wires is taken into account. The condition $H_L \geq H_s$ gives a threshold current I_0 :

$$I_0 = 2\pi h H_s \left\{ 1 + 2 \sum_m (-1)^m [(m\Lambda/2h)^2 + 1]^{-1} \right\}^{-1} \quad (16)$$

The photographs in Fig. 7 show the TM output vs. current in the circuit when the film is directly against the wires (picture A) and when a piece of paper about 6 mils thick is sandwiched in between. The threshold current is seen to be ~ 0.3 A and ~ 1 A, respectively. Using the values 200 and 400 microns for the parameter h , which corresponds roughly to the physical dimensions of the wire and the paper spacer, Eq. (16) gives 0.13 A and 0.77 A, in reasonable agreement with experimental values considering the crudeness of the model.

By varying the number of periods activated in the electrical circuit, keeping the current constant, we have tested the validity of the matrix formulation discussed in section II. As shown in Fig. 8, excellent agreement between experiment and theory is obtained for the $TE_5 \rightarrow TM_5$ mode conversion, with an "effective" optical rotatory power γ of $150^\circ/\text{cm}$. The intrinsic value of γ is believed to be somewhat higher since, as noted earlier, some fraction of the total interaction length remains unused. A reasonable agreement was also obtained (see Fig. 9) for the two immediately adjacent sets of modes; their measured mismatch Δn_g was 1.4×10^{-3} and 9.2×10^{-4} for the mode order $N = 6$ and 4, respectively.

III. 2. PERIODIC PERMALLOY STRUCTURE

In this study, we used a magneto-optic film of same composition as before, but of thickness $6.4 \mu\text{m}$. Our experiments concern TE and TM modes of order $N = 3$, which had a measured mismatch Δn_g of $(1.25 \pm 0.2) \times 10^{-3}$.

The periodic reversal of magnetization was accomplished by a novel technique, which features a periodic permalloy structure deposited on a transparent wafer brought in close proximity to the magneto-optic film. By properly biasing the device with an externally applied magnetic field, we have observed a DC conversion efficiency of $(80 \pm 2)\%$. The preliminary results of our investigation was summarized in a paper, to be submitted for publication in Applied Physics Letters, which is enclosed at the end of this report under the title, "Mode Conversion in Magneto-Optic Waveguides Subjected to a Periodic Permalloy Structure", and which we refer to at this point.

IV. CONCLUSIONS

In the first quarter, we reported that a maximum TE $\leftrightarrow$ TM mode conversion efficiency of only $\sim 1\%$ was observed in the $(\text{Gd}_{.5}\text{Y}_{2.5})(\text{Fe}_4\text{Ga}_1)\text{O}_{12}$ garnet thin film waveguide grown at IBM Research.

During this second quarter, we have successfully raised the efficiency, by periodically reversing the magnetization in the film guide, to 92% and 80% respectively, with two different device implementations: the first one utilizes an electrical serpentine circuit, and the other a novel periodic permalloy structure.

Both devices can be used as optical switches and modulators. However, further study on their switching speed has to be pursued.

For applications such as isolators and gyrators,⁵ the permalloy structure may prove to be advantageous since, unlike the serpentine circuit, it does not require a constant supply of electric current.

Further studies on the permalloy structure will be aimed at:

- (i) high speed switching
- (ii) improvement of conversion efficiency to above 90%
- (iii) correlation of magnetic domain structure with optimum conversion conditions.

V. FINANCIAL STATEMENT

Contract N00014-73-C-0256

<u>Total Contract Amount</u>	<u>Inception to Date Expenditures</u>	<u>Unexpended Funds</u>
\$99,000	\$46,269.49	\$52,730.51

Required Level of Effort
4077 hrs.

Inception to Date
Level of Effort
2,182 hrs.

REFERENCES

- 1) P. K. Tien, R. J. Martin, R. Wolfe, R. C. McCraw and S. L. Blank, Appl. Phys. Letters, 21, 394 (1972).
- 2) W. J. Tabor and F. S. Chen, J. Appl. Phys., 40, 2760 (1969).
- 3) T. P. Sosnowski and H. P. Weber, Optics Commun., 7, 47 (1973).
- 4) S. C. C. Tseng and A. Reisinger, Quarterly Technical Report, (15 January 1973 - 15 April 1973), June 1973.
- 5) J. Warner and T. G. Giallorenzi, "ARPA-NRL Infrared Integrated Optics Program", Quarterly Technical Report to Advanced Research Projects Agency, (1 December 1972 - 1 March 1973), April 1973.

APPENDIX

In the matrix formulation, the mode conversion efficiency is obtained from Eqs. (2) and (3) after setting $E_y(0) = 0$:

$$|E_y(z)|/E_x(0) = |\sin \chi| \sin \phi/2 \quad (A1)$$

where:

$$\phi = \Delta\beta \cdot z \quad (A2)$$

$$\sin \chi = (2\alpha)/(1 + \alpha^2) \quad (A3)$$

$$\alpha = (2\delta)/[(\epsilon_x - \epsilon_y) - [(\epsilon_x - \epsilon_y)^2 + 4\delta^2]^{1/2}] \quad (A4)$$

$\Delta\beta = \beta_+ - \beta_-$ is the difference in the propagation constants of the two normal modes such that:²

$$\beta_+^2 - \beta_-^2 = k_o^2 [(\epsilon_x - \epsilon_y)^2 + 4\delta^2]^{1/2} \quad (A5)$$

where k_o is the free-space propagation constant. Setting $\beta_+ + \beta_- = 2k_o \bar{n}$, where $\bar{n}$ is the average refractive index of the magneto-optic material, Eq. (A5) can be rewritten as:

$$\Delta\beta = \beta_+ - \beta_- = (\delta k_o / 2\bar{n}) \{ [(\epsilon_x - \epsilon_y)/2\delta]^2 + 1 \}^{1/2} \quad (A6)$$

The optical rotatory power γ is related to the off-diagonal element δ of the dielectric tensor by:¹

$$\gamma = (k_o \delta) / 2\bar{n} \quad (A7)$$

Let us define a coefficient B such that:

$$B \equiv \Delta\beta / 2\gamma$$

The quantity $(\epsilon_x - \epsilon_y)/2\delta$ appearing in Eq. (A6) can be transformed:

$$(\epsilon_x - \epsilon_y)/2\delta \approx (n_x - n_y)2\bar{n} \approx \Delta\beta/2[k_0\delta/2\bar{n}] = \Delta\beta/2\gamma = B \quad (\text{A8})$$

It follows from Eqs. (A2), (A6), (A7) and (A8) that:

$$\sin \phi/2 = \sin [\gamma z (1 + B^2)^{1/2}] \quad (\text{A9})$$

Combining Eqs. (A4) and (A8), one has:

$$\alpha \approx 1/[B - (1 + B^2)^{1/2}]$$

thus

$$1 + \alpha^2 = [2(1 + B^2)^{1/2}]/[(1 + B^2)^{1/2} - B]$$

and

$$|\sin \chi| = 2|\alpha|/(1 + \alpha^2) = (1 + B^2)^{1/2} \quad (\text{A10})$$

Substituting (A9) and (A10) back into (A1) leads to:

$$|E_y(z)|/E_x(0) = (1 + B^2)^{-1/2} \sin [\gamma z (1 + B^2)^{1/2}] \quad (\text{A11})$$

where one recognizes the standard result derived from coupled mode theory.³

FIGURE CAPTIONS

- 1) Schematic of electrical serpentine circuit.
- 2) TE output modulation. Lower trace is 60-Hz AC current, with a scale of 1.5 amp/vertical division. Middle trace is zero line, indicating a depletion ratio of 82%.
- 3) 60-Hz and 120-Hz signal vs. analyzer azimuth. Theoretical dependence is $\sin 2\theta$ and $\cos 2\theta$, respectively.
- 4) B-H curve of magneto-optic waveguide for two orthogonal directions in the plane of the film.
- 5) Illustration of partial magnetization of film.
- 6) Conversion efficiency vs. current in an 8-period circuit.
- 7) Oscillographs of TM signal vs current: (a) film directly against serpentine circuit; (b) 6-mil spacer sandwiched in between.
- 8) $TE_5 \rightarrow TM_5$ conversion efficiency vs. number of periods. Full circles are experimental data. Solid curve is theory with an effective rotatory power of $150^\circ/\text{cm}$.
- 9) Conversion efficiency vs. number of periods: (a) $TE_6 \rightarrow TM_6$; (b) $TE_4 \rightarrow TM_4$. Solid line is the theoretical curve.

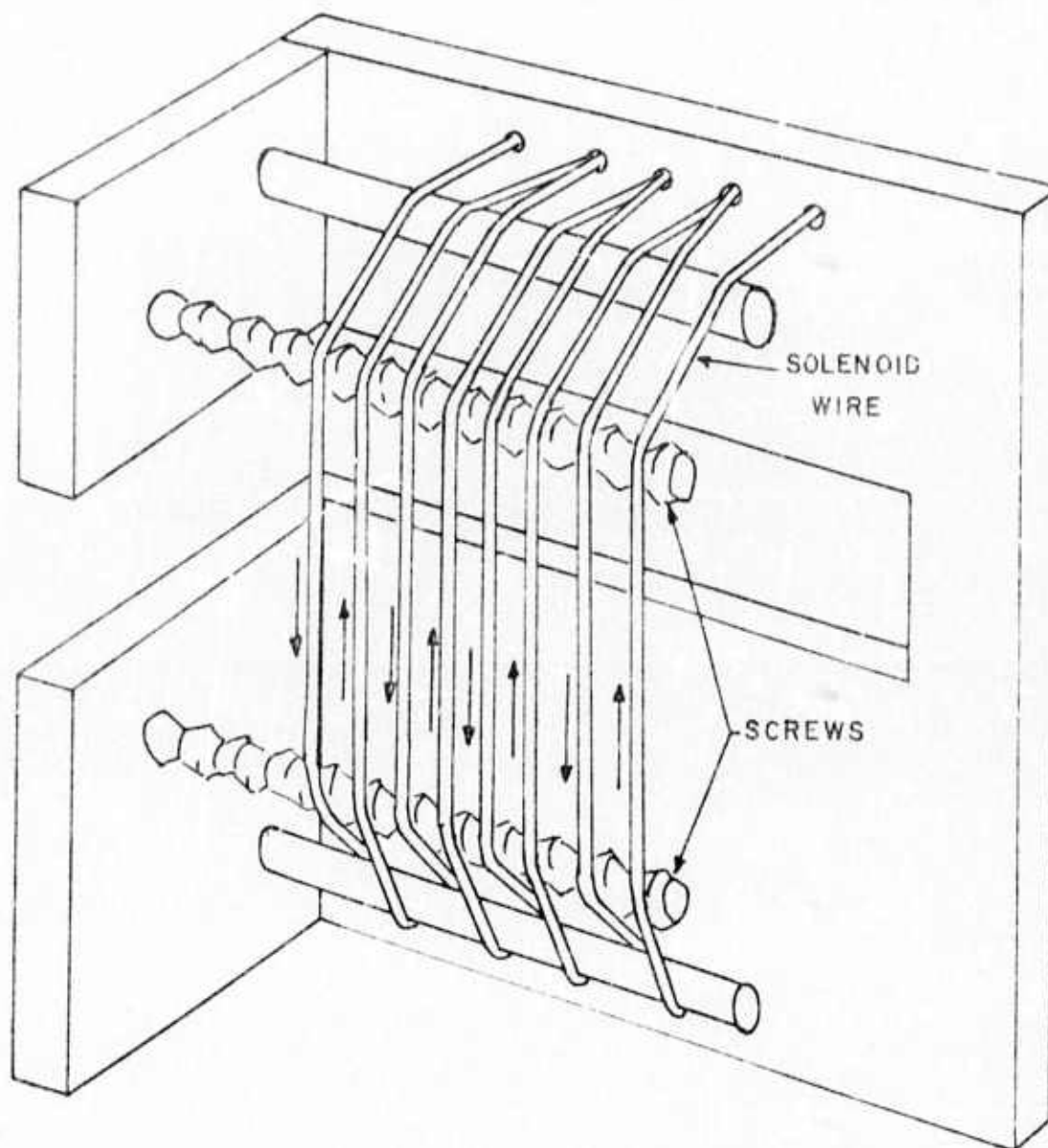


Fig. 1

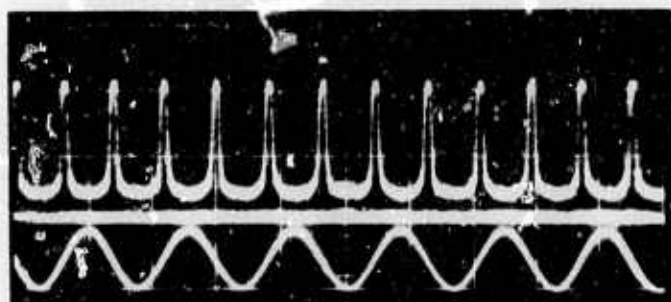


Fig. 2

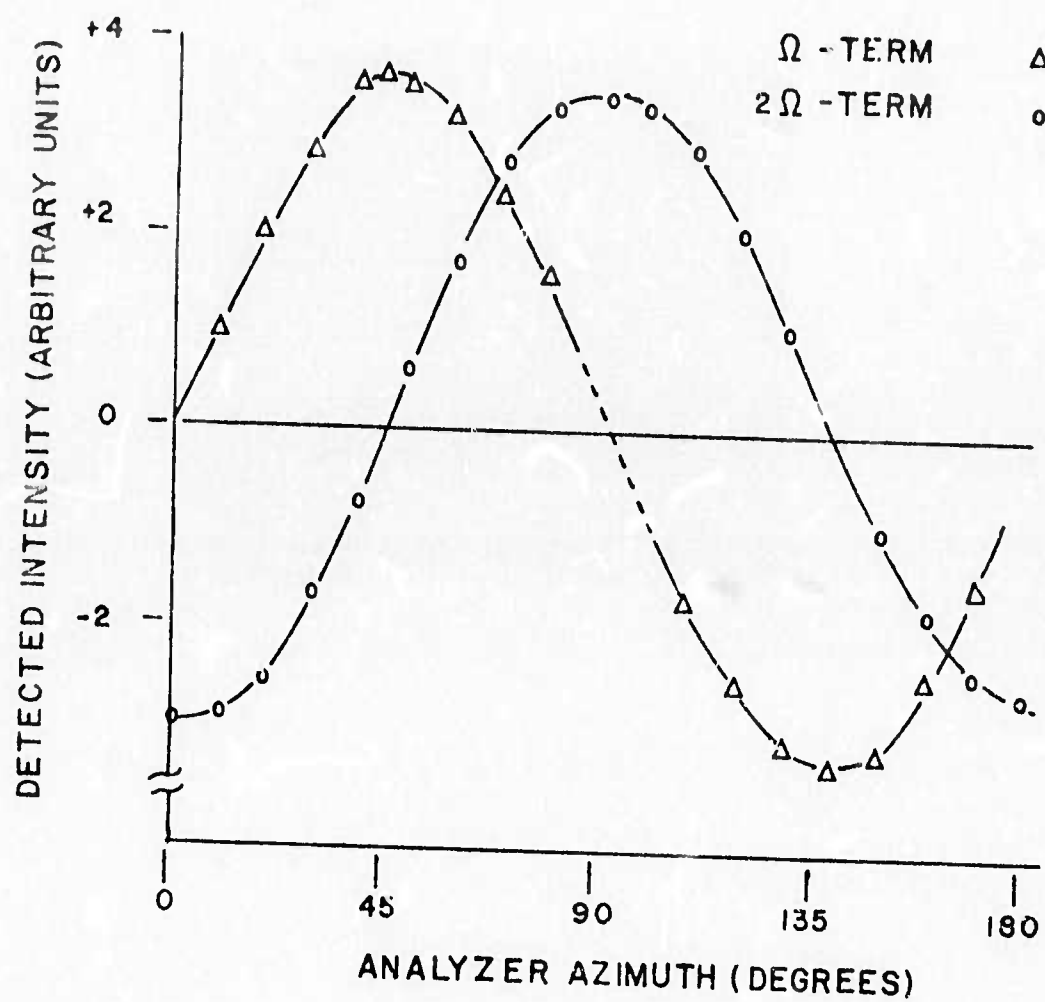


Fig. 3

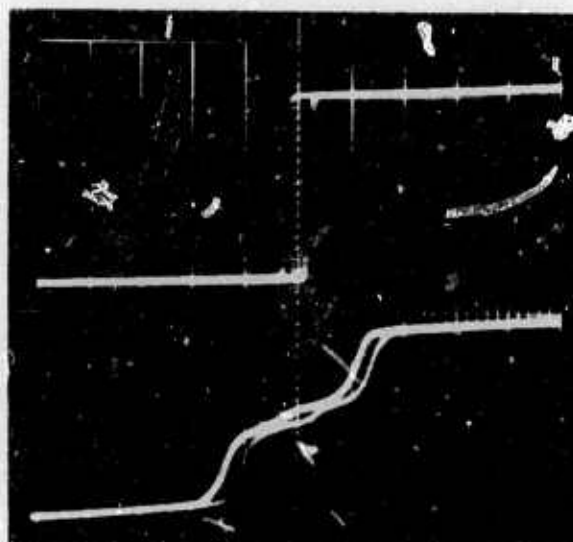


Fig. 4

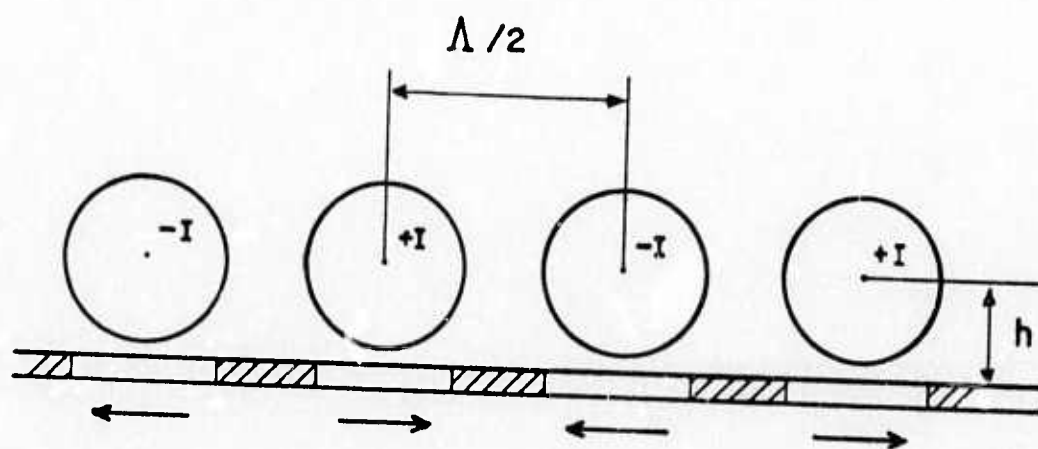


Fig. 5

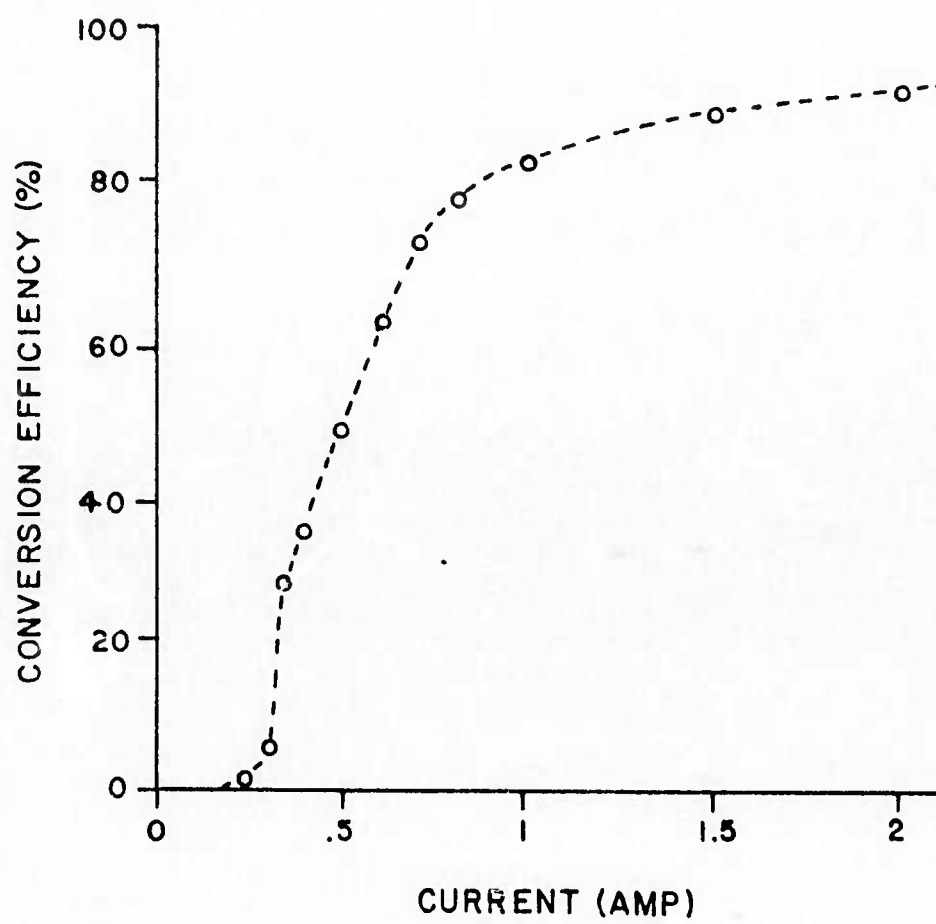
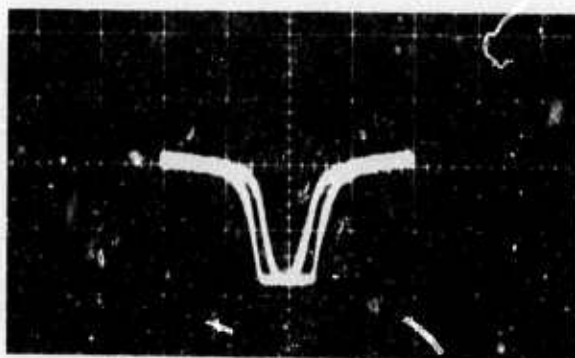


Fig. 6

A



B



Fig. 7

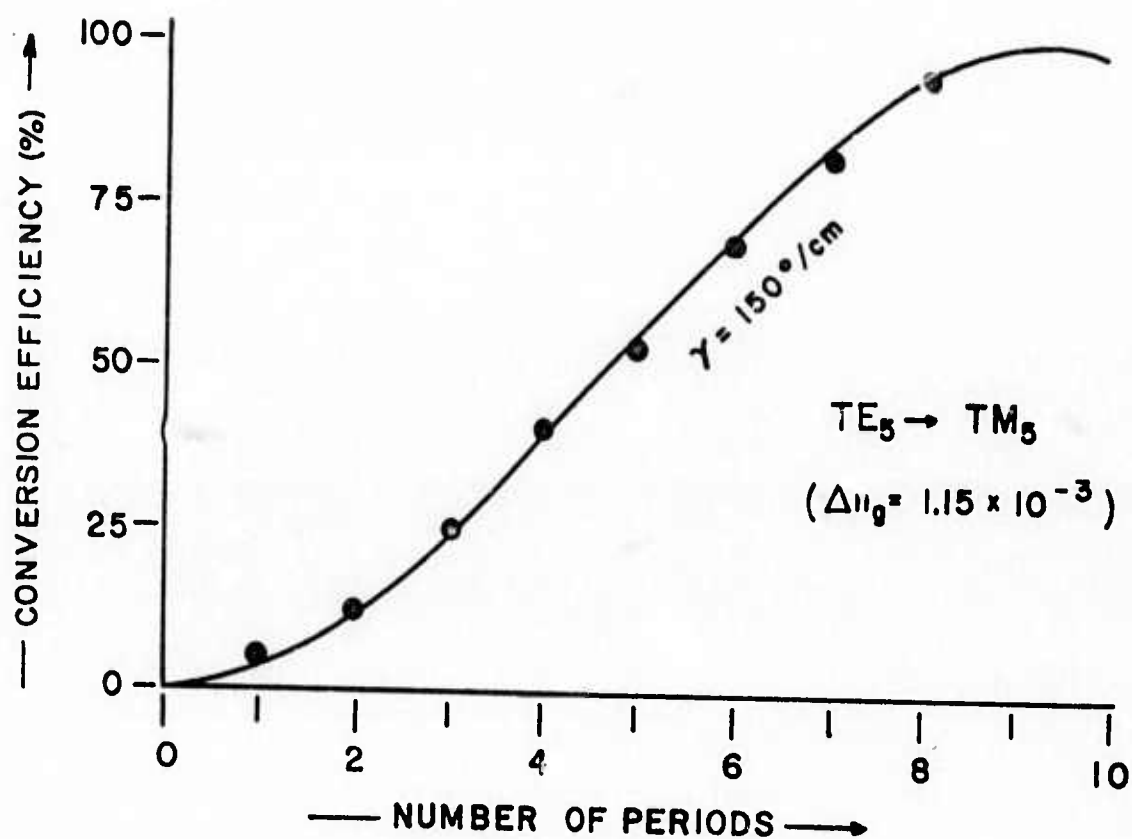


Fig. 8

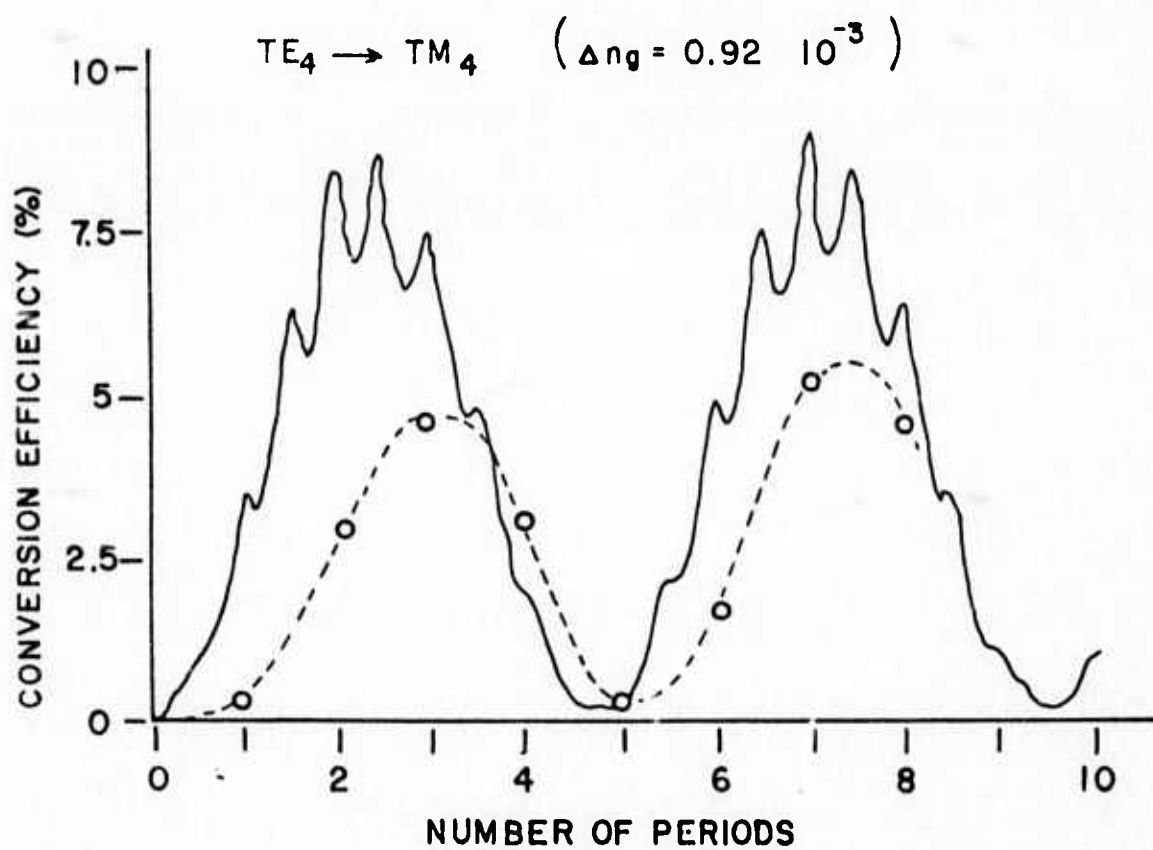
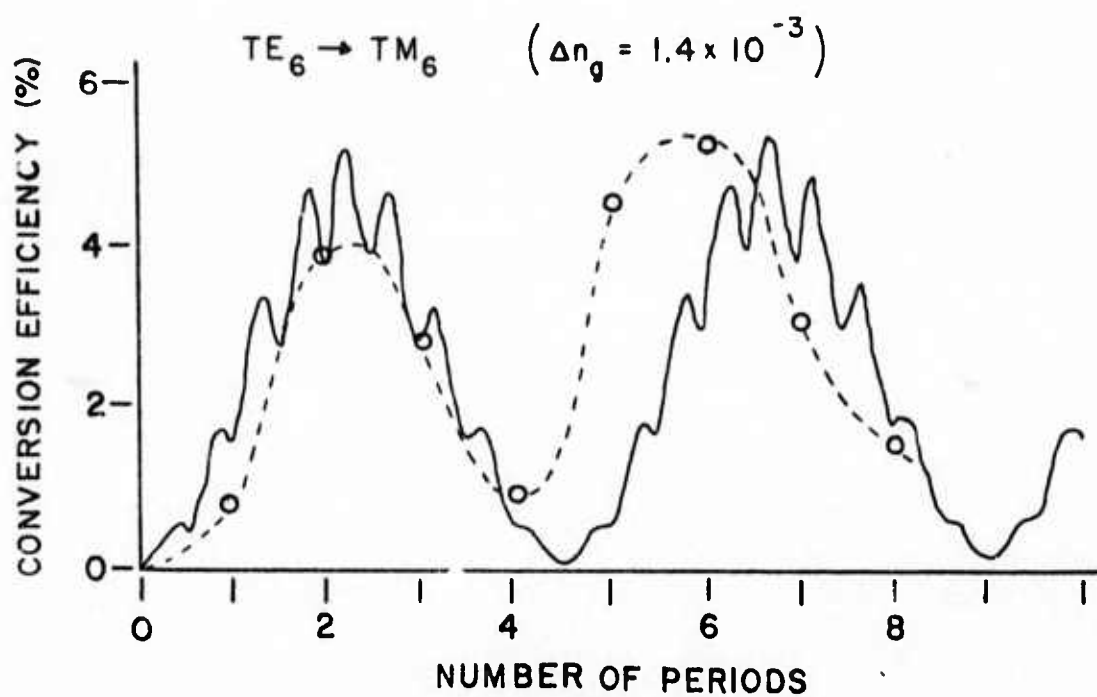


Fig. 9

ACKNOWLEDGEMENT

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by ONR under Contract No. N00014-73-C-0256.

MODE CONVERSION IN MAGNETO-OPTIC WAVEGUIDES
SUBJECTED TO A PERIODIC PERMALLOY STRUCTURE

by

S. C.-C. Tseng
A. R. Reisinger
E. A. Giess
C. G. Powell

IBM Thomas J. Watson Research Center
Yorktown Heights, New York

ABSTRACT

A new method to achieve periodic reversals of magnetization, necessary to attain high mode conversion efficiencies in magneto-optic waveguides, is described. It is accomplished by means of a periodic permalloy structure overlaying the optical propagation path. With proper bias fields, we have observed an optimum DC conversion efficiency of $(80 \pm 2)\%$ at $1.15 \mu\text{m}$ in a $\text{Gd}_{0.5}\text{Ga}_1$ iron garnet film guide.

This work is supported by Advanced Research Projects Agency, under contract #N00014-73-C-0256.

The efficiency of the mode conversion process in magneto-optic thin film waveguides grown on isotropic substrates is limited to typically a few percent, due to the mismatch between the phase velocities of TE and TM modes. It is known that this limitation can be overcome by periodically reversing the magnetic domains along the direction of propagation of light at locations where the phase difference between "free" and "forced" waves reaches 180° or a multiple thereof.¹ This principle was implemented by Tien et al¹ in the form of an electrical serpentine circuit with appropriate periodicity.

In this letter, we report a new method to achieve the desired periodic reversal of magnetic field. It is accomplished by means of rectangular islands of permalloy deposited in a periodic pattern on a transparent wafer. The structure is equivalent to a chain of small permanent magnets, giving rise to an external magnetic field that is spatially modulated in sign and amplitude.

The experimental arrangement is shown in Fig. 1. The magneto-optic waveguide was a $(\text{Gd}_{.5}\text{Y}_{2.5}\text{Fe}_4\text{Ga}_1)\text{O}_{12}$ film grown by liquid phase epitaxy on a chemically polished GGG substrate. The magnetization lay in the plane of the film, with a measured $4\pi M$ of ~ 200 Gauss. Input and output grating couplers, with a period of $1.2 \mu\text{m}$, were fabricated on the film's surface.

The $1.15 \mu\text{m}$ output of a He-Ne laser was coupled in the film, which had a thickness of $6.4 \mu\text{m}$ and an index of 2.14. The experiments described below concern TE and TM modes of order $N=3$. By simultaneously

exciting both these modes and measuring the angular separation of the two outputs, the mismatch $\Delta\beta$ between the propagation constants was estimated to be $\Delta\beta = (68 \pm 11) \text{ cm}^{-1}$, meaning that the longitudinal magnetic field should be reversed every 18 mils ($\pi/\Delta\beta$).

To provide this periodic reversal, a permalloy film approximately 3500 Å thick, was sputtered on a c-cut sapphire wafer and photolithographically etched into a periodic array of rectangular islands. The dimensions of the rectangles were 18 mils and 36 mils in the longitudinal and transverse directions, respectively, with a periodicity $\Lambda = 36 \text{ mils}$.² The resultant structure was then brought in contact with the waveguide, the permalloy facing the film, and the two pieces were gently clamped together.

The TE_3 mode was excited at the input grating and the output was investigated under the following different conditions: (i) optimum D.C. bias for maximum conversion, (ii) A.C. field in addition to the D.C. bias, and (iii) zero field. In these experiments, the interaction length was 9 mm, corresponding to 10 periods of the permalloy structure.

(i) Optimum D.C. Bias. Two sets of Helmholtz coils were used to apply external D.C. magnetic fields in both longitudinal and transverse directions, as shown in Fig. 1. Although conversion occurred over a fairly wide range of applied magnetic field intensities, the optimum result was obtained with 1 Oe in the longitudinal and 2.4 Oe in the transverse direction, as measured with a gaussmeter probe (with zero current in the coils, the stray magnetic field was found

to be -0.15 Oe longitudinal and -0.5 Oe transverse). Fig. 2a shows the TE_3 output when the device was subjected to the stray magnetic field alone. Under the optimum bias conditions, the TE_3 output was considerably depleted and most of the energy emerged in the TM_3 mode, as evidenced in Fig. 2b. The measured conversion efficiency was $(80 \pm 2)\%$.

The mode conversion process can be described by:³

$$\begin{bmatrix} E^{TE}(L) \\ E^{TM}(L) \end{bmatrix} = T^+ \left(\frac{\Lambda}{2}\right) T^- \left(\frac{\Lambda}{2}\right) T^+ \left(\frac{\Lambda}{2}\right) T^- \left(\frac{\Lambda}{2}\right) \cdots \begin{bmatrix} E^{TE}(0) \\ E^{TM}(0) \end{bmatrix} \quad (1)$$

where $T^+ (\Lambda/2)$ and $T^- (\Lambda/2)$ are the transmission matrices describing propagation over a half period $(\Lambda/2) = \pi/\Delta\beta$ for a longitudinal field in the positive and negative directions, respectively. These matrices are defined by:

$$T^+ (\Lambda/2) = \begin{bmatrix} -j \cos \chi & -\sin \chi \\ \sin \chi & j \cos \chi \end{bmatrix}, \quad T^- (\Lambda/2) = \begin{bmatrix} -j \cos \chi & \sin \chi \\ -\sin \chi & j \cos \chi \end{bmatrix}$$

where $\chi = 2\gamma/\Delta\beta$, γ being the coupling coefficient, or optical rotatory power. For a total distance $L = 10\Lambda$, the matrix product (T^+, T^-) repeats itself 10 times. Setting $E^{TM}(0) = 0$ at the input, we have $E^{TE}(10\Lambda) = E^{TE}(0) \cos(20 \chi)$ and $E^{TM}(10\Lambda) = -j E^{TE}(0) \sin(20 \chi)$. A conversion efficiency of 80% leads to an effective rotatory power γ of $110^\circ/\text{cm}$ and an off-diagonal permittivity ϵ_{12} in the order of

1.4×10^4 . Eq. (1) is found to fit the experiment reasonably well when the number of periods was varied along the propagation path. The fact that the conversion efficiency began to decrease for an interaction length beyond 10 periods can probably be ascribed to a slight deviation of the periodicity Λ from its ideal value $2\pi/\Delta\beta$. We believe that a more accurate choice of periodicity could result in a still higher efficiency.

We also observed that the mode conversion disappeared when either one of the externally applied fields became too strong (exceeding about 5 Oe longitudinal and 10 Oe transverse). It is attributed to the fact that too strong a longitudinal field tends to override the periodic field created by the permalloy structure, whereas a strong transverse field will align the moments in a direction that does not induce conversion.

(ii) A.C. Field in Addition to D.C. Bias. With a D.C. bias of 1.4 Oe longitudinal and 2.1 Oe transverse, an A.C. field was superposed in the transverse direction. Fig. 3 shows the TE_3 and TM_3 outputs, with a TE_3 modulation ratio about 70% for an A.C. field of 2.9 Oe r.m.s. at 60 Hz. It is not entirely clear why the efficiency was slightly lower than in the D.C. experiment.

(iii) Zero Field. In this experiment, the two sets of coils were used to cancel the stray fields to zero at the site where the device was subsequently mounted. No mode conversion was observed in this initially relaxed state. When a D.C. magnetic field was applied in the transverse direction and then gradually reduced to

zero, we observed a conversion of about 48% which persisted indefinitely until a transient perturbing field was applied. No similar effect occurred when the D.C. field was applied in the longitudinal direction and then reduced to zero.

Although a complete understanding of these results would require a detailed knowledge of the domain structures of both the permalloy and the garnet film, our interpretation is as follows. Prior to etching, the permalloy layer did not exhibit any preferred direction in its plane. However, the shape anisotropy of the periodic structure obtained after etching creates an easy axis in the transverse direction (the transverse dimension of each rectangle is twice as large as the longitudinal one). A correspondingly stronger demagnetizing field may prevent the periodic structure from remaining magnetized longitudinally at zero applied field. By contrast, a transverse D.C. field will first saturate all the permalloy islands in that direction; as the field is reduced to zero, it is possible that the structure may relax from the parallel to an antiparallel configuration, thereby reducing the magnetostatic energy. If so, a periodically reversed longitudinal field will exist in the regions between the permalloy islands, while a transverse field will prevail directly underneath them. Since only half the total length (regions with longitudinal field) contributes to mode conversion, the efficiency is expected to be reduced by a factor of $1/2$. This was approximately the case in our experiment.

Finally, it can be calculated that the decay constant of the

evanescent field protruding outside the magnetic waveguide is about $1000 \text{ \AA}$. It is, therefore, unlikely that the mode conversion takes place in the permalloy itself, rather than in the garnet film. In an attempt to verify this contention, we sandwiched a piece of black paper, 5 mils thick, between the permalloy structure and the film. Under these conditions, we still observed a conversion efficiency of 15%, despite the reduction in intensity of the field sensed by the magnetic waveguide.

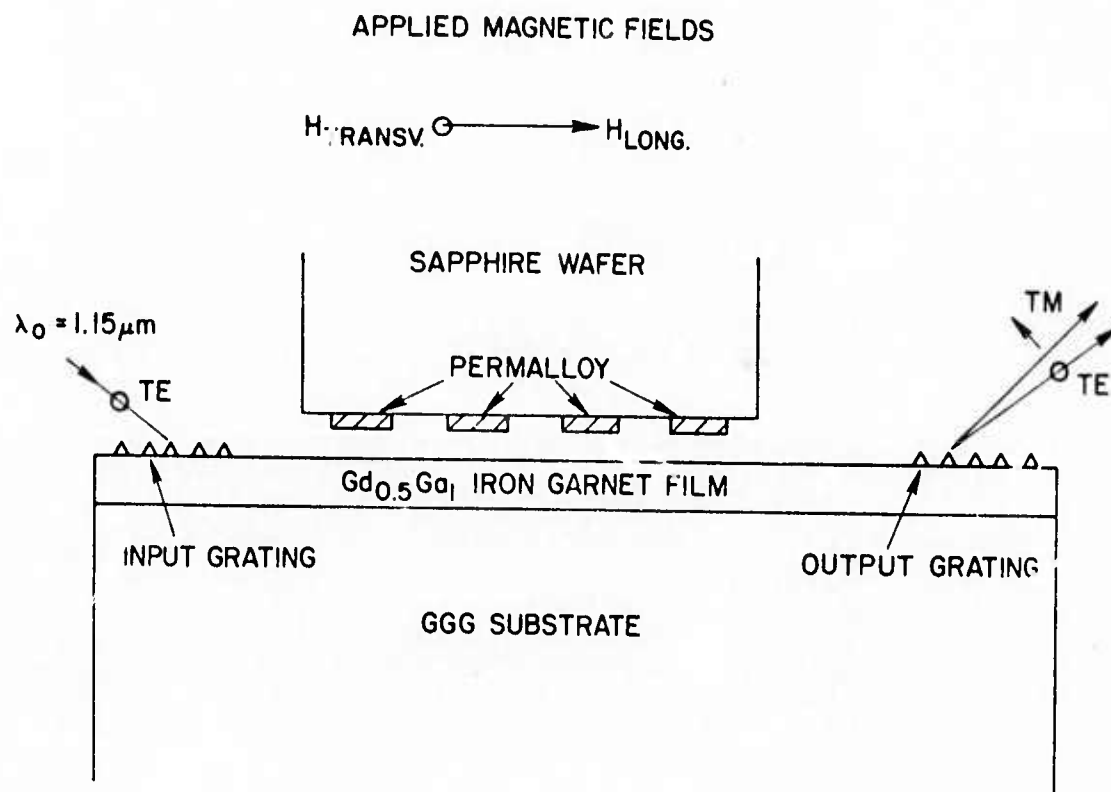
In conclusion, we have observed efficient mode conversion in a magneto-optic film waveguide subjected to the magnetic field generated by a periodic permalloy structure. The coils used in these experiments to apply D.C. bias fields could certainly be replaced by small permanent magnets. This solution would be more compatible with integrated optical technology and would permit efficient D.C. conversion without any need for electrical currents. In addition to A.C. modulation, the existence of mode conversion over a finite range of applied magnetic fields may lead to interesting coincident switch applications.

REFERENCES

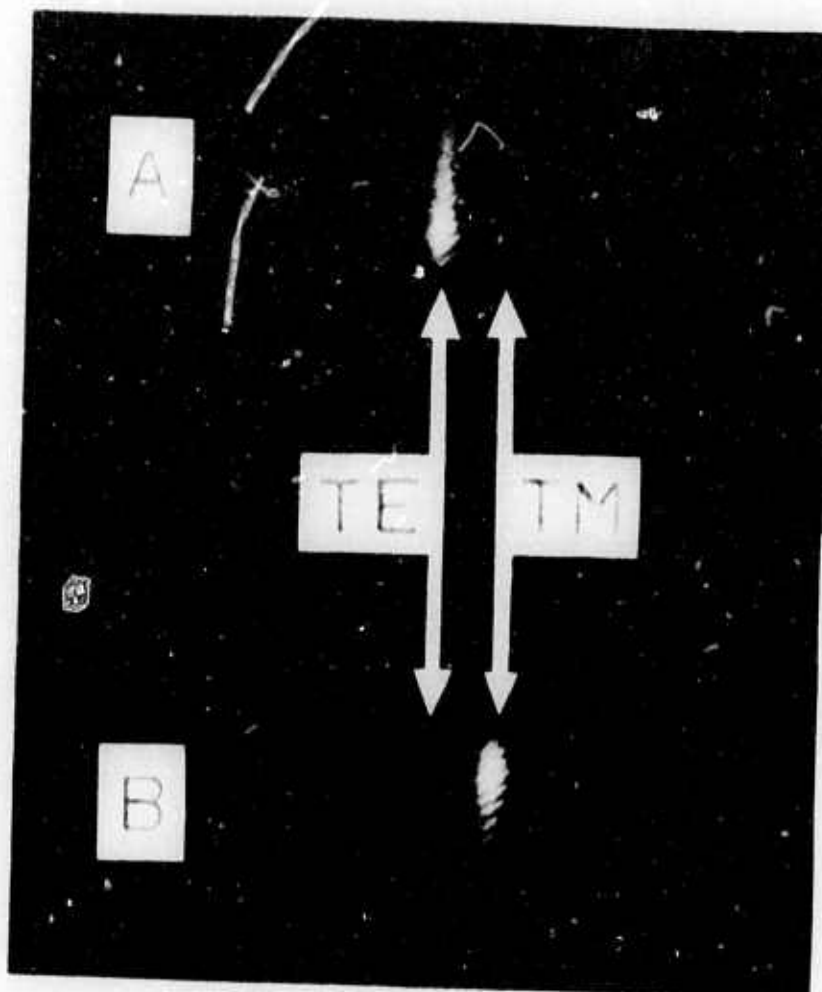
- 1) P. K. Tien, R. J. Martin, R. Wolfe, R. C. LeCraw and S. L. Blank, Appl. Phys. Lett. 21, 394 (1972).
- 2) While the longitudinal dimension of 18 mils is derived from calculation, the transverse size is chosen arbitrarily to cover the optical beam width.
- 3) W. J. Tabor and F. S. Chen, J. Appl. Phys. 40, 2760 (June 1969).

FIGURE CAPTIONS

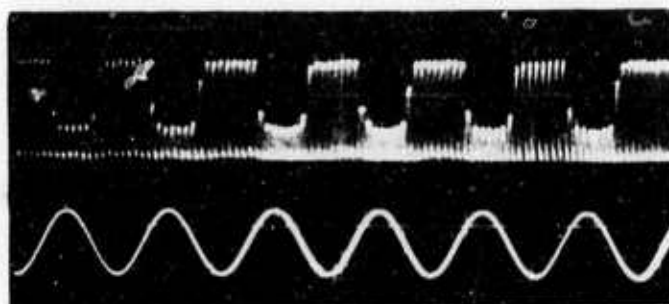
- 1) Experimental configuration.
- 2) Far field radiation emerging from the output grating.
(a) unconverted TE_3 output; (b) depleted TE_3 and converted TM_3 modes under D.C. magnetic field bias of 1.0 Oe longitudinal and 2.4 Oe transverse.
- 3) 60-Hz modulated outputs of TE_3 (a) and TM_3 (b) modes. The 900-Hz modulation is the chopping frequency. D.C. bias is 1.4 Oe longitudinal and 2.1 Oe transverse. Lower traces proportional to superposed transverse A.C. field of 2.9 Oe r.m.s.



- Fig. 1 -



A



B

