Polycrystalline–Metal–Ferromagnetic Optical Waveguide Isolator (POWI) for Monolithic-Integration with Diode-Laser Devices

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Abstract—**Optical Faraday rotation in polycrystalline or amorphous thin films of ferromagnetic materials can be used to obtain true-optical isolators and nonreciprocal-TE–TM-mode converters which cover a wide wavelength range. These can be integrated with semiconductor lasers and other integrated optic devices because the films do not require epitaxial deposition. A detailed description and analysis of an integrable isolator with better than 30-dB isolation ratio and low insertion loss in the 1.5-μm wavelength region is given.**

Index Terms—**Integrated optics, isolators, magnetooptic isolators, optical communication, optical isolators, optics, semiconductor lasers, semiconductor optical amplifiers.**

I. Introduction

We PROPOSE and theoretically investigate a novel and powerful approach for achieving true-optical isolators and nonreciprocal-TE–TM-mode converters which can be integrated with semiconductor lasers and other integrated optic devices. The strong optical Faraday rotation in polycrystalline or amorphous thin films of ferromagnetic materials such as iron, nickel, and alloys is used. These films may be nonepitaxially deposited on semiconductor and insulating material systems. A wide wavelength range extending from the visible through the near infrared can be covered.

Such integrable-isolator/mode converters have not been reported before and will extend the benefits of integration to waveguide devices ranging from communication types of diode lasers to high power laser arrays and amplifiers. A specific design of an integrable isolator using an amorphous layer of iron, operating at 1.54 μm, having an operating current of 86 mA, a length of 1.2 mm, an isolation ratio <-30 dB, and insertion loss <1 dB is described and analyzed as an example.

II. Design Details

The principles of waveguide isolators based on Faraday rotation are well known (e.g., see [1]). The devices consist of an input polarization mode analyzer, a nonreciprocal TE–TM mode converter, a reciprocal mode converter, and an output polarization analyzer. Absence of a suitable nonreciprocal mode converter has prevented integration of isolators in the past. This letter gives a detailed description of our novel and integrable, nonreciprocal, Polycrystalline/amorphous Ferromagnetic TE–TM Mode Converter (PFMC) illustrated in Fig. 1. A cross section in the x–z plane is shown. The layers form a waveguide with gain provided by a semiconducting-quantum-well amplifier. Propagation is in the z direction. The 1000-Å thick amorphous/polycrystalline ferromagnetic (iron, nickel, etc.) layer can be deposited by many well known methods on almost any semiconducting system. The ferromagnetic layer provides the Faraday rotation and also makes the p-contact which is completed by the ≈2000-Å-thick gold layer. The use of Nickel for semiconducting laser contacts has been reported [2].

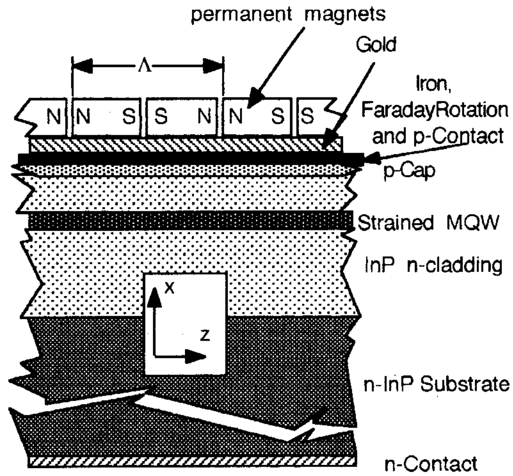

Fig. 1. Cross section of Polycrystalline/amorphous Ferromagnetic TE–TM Mode Converter (PFMC). The 1000-Å-thick iron layer provides both the Faraday rotation and part of the p-contact.

A thin p-clad (3000-Å thick) is used. This gives sufficient optical field overlap in the iron film to provide strong Faraday effect coupling between the TE and the TM mode. The refractive indexes and the layer thickness used in the calculation are given in Table I [3]–[7].

The required magnetic field in the z direction may be provided by permanent magnets with periodic field reversal ($\Lambda \approx 66$) μm chosen to obtain phase match between the TE and TM modes [8], [9]. Sufficient magnetic field to saturate the thin iron film is assumed. A suitable thin-film magnet is described in [10]. The field reversal will be discussed further below.

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TABLE I

PFMC LAYERS. SEMICONDUCTING REFRACTIVE INDEXES FROM ADACHI [3] AND HENRY *et al.* [4]. REFRACTIVE INDEXES OF GOLD AND IRON FROM [5] AND [6]. THE VALUES SHOWN ARE FOR THE WAVELENGTH $\lambda = 1.54\ \mu m$

Layer	n, real part of refractive index	k, imaginary part of index, +=loss, (-)=gain	Layer Thickness (μm)
Gold p-contact	0.172	+10.14	2.000
Iron p-contact provides Faraday Rotation	3.62	+5.64	0.100
InGaAsP "cap"	3.4137	0.00	0.050
InP p-clad	3.1633	0.00	0.300
Four (4) InGaAsP barriers* alternating	3.4132	0.00	0.027
with three (3) InGaAs Strained QWs**	3.5298	Varied (-), see Table 2	0.016
InP n-clad and substrate	3.1637	0.00	>50
n-contact	------------	--------------	-----------

A 2.5-μm-wide ridge is used to form the lateral (y) waveguide [11]. The drive current calculated below is obtained assuming that the ridge and lateral contact dimensions are chosen so that the current and optical field fully overlap in the y direction.

III. THEORY

We will restrict our discussion to the case of a TE mode isolator. Similar expressions can be obtained for a TM mode isolator by simple substitution. The isolation ratio, I_R, is defined in terms of the TE and TM powers as follows:

$$I_R = \frac{P_e^-}{P_{eo}} L_R. \tag{1}$$

L_R is the insertion loss ratio given by

$$L_R = \frac{P_e + P_m - |P_e - P_m|}{P_{eo}}. \tag{2}$$

The input optical mode power is P_{eo}. The power emerging from the PFMC in the forward direction is $P_e(P_m)$, and the reflected power leaving the section in the backward direction is $P_e^-(P_m^-)$. Subscripts e, m refer to the TE, TM modes, respectively. An ideal nonreciprocal TE–TM converter portion of a waveguide isolator would have an output of equal TE and TM power for an input of 100% TE power in the forward direction and an output of 100% TM power for an input of equal TE and TM powers in the reverse direction.

Gain is needed to compensate for the high optical loss of the amorphous/polycrystalline ferromagnetic layers. Because of dispersion in the complex index of refraction, optimum operation requires different TE and TM gains. Higher TM losses require greater TM than TE gain. Strained quantum wells can be used to vary the TE to TM gain ratio. Compressively strained wells give greater TE than TM gain while tensile strained wells give greater TM than TE gain [12]. An amplifier with tensile strained wells, similar to the multiquantum-well (MQW), diode-laser amplifier reported by Miller *et al.* [7], would be suitable and is used as a model in our analysis.

TABLE II

IMAGINARY PART OF INDEX [(−) = GAIN] PER QUANTUM WELL. VALUES CALCULATED FROM EXPERIMENTAL MEASUREMENT OF INTERNAL GAIN [7] AS A FUNCTION OF CURRENT PER UNIT LENGTH OF INTERACTION. THE VALUES SHOWN ARE AT $\lambda = 1.54\ \mu m$

Current, I (mA/mm)	Imaginary part of refractive index for each quantum well, TE mode	Imaginary part of refractive index for each quantum well, TM mode
60	(-)0.0145	(-)0.213
61	(-)0.0150	(-)0.219
62	(-)0.0152	(-)0.225

TABLE III

CONSTANTS FOR THE GUIDED MODES. REAL PART OF THE REFRACTIVE INDEX n_e, n_m, IMAGINARY PART OF THE REFRACTIVE INDEX k_e, k_m, (−)GAIN, (+) LOSS; THE GAIN/LOSS COEFFICIENT α_e, α_m, (−) GAIN, (+) LOSS

I mA/mm	n_e TE	n_m TM	$k_e \times 10^5$ TE	$k_m \times 10^4$ TM	$\alpha_e \times 10^4$ (μm^{-1}) TE	$\alpha_m \times 10^4$ (μm^{-1}) TM
60	3.19337	3.17004	+15.6562	+1.3379	+6.3877	+5.4587
61	3.19337	3.17008	+2.6966	(-)1.2262	+1.1002	(-)5.0029
62	3.19337	3.17012	+0.15996	(-)3.6981	+0.0653	(-)15.0884

The imaginary part of the refractive index (gain) for each quantum well for both the TE and TM modes is computed from the measured internal gain of the MQW amplifier ([7, Fig. 5]). The wavelength is 1.54 μm. The results for currents of 60, 61, and 62 mA/mm are shown in Table II. Optimum TE–TM mode conversion is obtained at 61 mA/mm. (See Table IV.)

The values shown in Tables I and II are used in a computer waveguide program [13] to calculate the complex refractive index for the guided mode, $n_{e,m} + k_{e,m}$. The modal gain/loss coefficient $\alpha_{e,m} = 2\pi k_{e,m}/\lambda$. The TE–TM coupling coefficient $\kappa_{em} = \Phi\Psi_{em}$. Φ is the Faraday rotation (in units of radians/length). $\Psi_{em}(= \Psi_{me})$ is the TE–TM field overlap in the ferromagnetic layer. We take the Faraday rotation for magnetically saturated iron (magnetic field parallel to the propagation direction) to be 2.09×10^5°/cm = 0.3648 rad/μm. [5]. For our thin iron layer, Ψ_{em} is closely approximated by $\sqrt{\Gamma_e \Gamma_m}$. Γ_e, Γ_m are the individual field overlaps of the TE, TM modes in the iron layer that we conveniently calculate from our waveguide program. The effective coupling coefficient $\kappa = \sqrt{\kappa_{em}^2 + \delta^2}$. δ is the phase mismatch given by $2\pi\,[(n_e - n_m)/\lambda + 1/\Lambda]$. It may be seen that a spatial periodicity in the interaction with period Λ can be used to reduce the phase mismatch [8]. A periodic reversal in the magnetic field [9] is used here. The constants are inserted in a numerical-coupled-mode calculation which includes gain-loss to find the modal powers as a function of propagation length [13]. The isolation ratios and insertion losses are calculated using (1) and (2).

IV. RESULTS

The calculated refractive indexes and gain/loss coefficients for the lowest order TE and TM modes are shown in Table III.

The calculated values of the TE–TM coupling coefficient, modal optical powers, insertion losses, and isolation ratios are shown in Table IV. The optimum PFMC length (L =

TABLE IV
THE COUPLING COEFFICIENT κ_{em}, MODAL OPTICAL POWERS P_e, P_m, P_e^-, P_m^-, FOR THREE CURRENTS AFTER PROPAGATION THROUGH A PFMC LENGTH OF 1.417 mm. THE RESULTING INSERTION LOSS RATIO, L_R, AND ISOLATION RATIO, I_R, VALUES SHOWN ARE CALCULATED FROM THESE POWERS USING (1) AND (2). THE TE INPUT OPTICAL POWER $P_{eo} = 1$. IN THE REVERSE DIRECTION THE REFLECTED TE POWER ENTERING THE PFMC IS ASSUMED TO BE 0.5 AND EQUAL TO THE REFLECTED TM POWER ENTERING THE PFMC. PERFECT PHASE MATCH AT EACH CURRENT IS ASSUMED

I mA/mm	κ_{em} x10⁴ (μm-1)	P_e Forward TE,	P_m Forward TM,	P^-_e Reverse TE,	P^-_m Reverse, TM,	L_R Loss Ratio	I_R Isolation Ratio,
60	3.7921	0.116	0.048	0.007	0.189	0.23	0.03 -15.2 dB
61	3.7956	0.481	0.482	1.20x10-7	3.1	0.96	>10-7 -70dB
62	3.7986	0.448	3.135	0.607	45.05	1.12 (gain)	0.544, -2.6dB

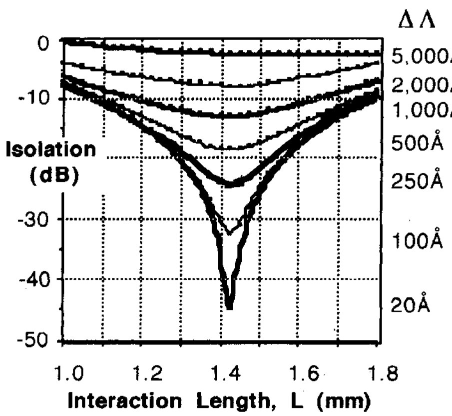

Fig. 2. Plot of isolation ratio versus interaction length with variation of magnetic field reversal period ($\Delta\Lambda$) as a parameter. To obtain −30 dB or better $\Delta\Lambda < \pm 100$ Å and the interaction length must be within ±30 μm, for −20 dB the tolerance is eased to $\Delta\Lambda < \pm 500$ Å and length <±100 μm, for −10 dB $\Delta\Lambda < \pm 1000$ Å and length <±200 μm.

1.417 mm) for a current of 61 mA/mm (86.4 mA) is used. Phase match is assumed for each current. Under these ideal conditions the insertion loss is negligible and there is a very high isolation ratio. For a fixed interaction length the output ratios will vary with current because the modal gains change rapidly as can be seen in Table III. In particular note that in going from 60 to 62 mA/mm (85.8 to 87.2 mA), α_e decreases by a factor ≈6 while α_m goes from a loss (+) to a gain (−).

For phase match, $\delta = 0$, a periodic reversal of magnetic field with $\Lambda = 66.1313$ μm is required. Plots of isolation ratio versus interaction length with variation of magnetic field reversal period $\Delta\Lambda = |66.1313 - \Lambda|$ as a parameter are shown in Fig. 2. Small variations in Λ and modest variation in interaction length result in large degradation of the isolation ratio. For an isolation ratio $I_R \approx -20$ dB $\Delta\Lambda$ must be $< \approx \pm 500$ Å, (±0.08%). −30 dB requires $< \approx \pm 100$ Å (±0.015%). Clearly structures with low dispersion would be be sought for use in optimized isolators to ease the tolerance. See [14]–[16] for examples.

Note, that the Faraday rotation in ferromagnetic metals extends over a wavelength range that includes the visible and near infrared. Thus, isolators can be designed for operation at any wavelength in this large region.

V. CONCLUSION

We have described and analyzed the first practical waveguide isolator which can be integrated with semiconductor lasers and other integrated optic devices. These are true isolators that can be used at wavelengths covering the visible and near infrared regions. Our novel approach uses a polycrystalline/amorphous layer of ferromagnetic material such as iron to provide the dual function of giving the required *nonreciprocal* Faraday rotation while simultaneously providing part of the electrical contact of a semiconductor amplifier. Because the layer does not require epitaxial growth, it can be deposited on a wide variety of materials used in diode laser and integrated optic technology.

REFERENCES

[1] R. Wolfe, "Magneto-optic waveguide isolator based on laser annealed (Bi, Ga) YIG films (invited)," *IEEE Trans. Magn.*, vol. MAG-21, pp. 1647–1650, Sept. 1985.

[2] C. H. Wu, P. S. Zory, and M. A. Emanuel, "Contact reflectivity effects on thin p-clad InGaAs single quantum well lasers," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 1427–1429, Dec. 1994.

[3] S. Adachi, "Optical properties of $In_{1-x}Ga_xP_{1-y}$ alloys," *Phys. Rev. B*, vol. 39, pp. 12612–12621, June 15, 1989.

[4] C. H. Henry, L. F. Johnson, R. A. Logan, and D.P. Clark, "Determination of the refractive index of InGaAsP epitaxial layers by mode line luminescence spectroscopy," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1887–1892, Dec. 1985.

[5] B. M. Bozorth, T. R. McGuire, and R. P. Hudson, "Magnetic properties of materials," in *American Institute of Physics Handbook*, 2nd ed. New York: McGraw Hill, 1963, table 5g-26, p. 5-212, table 6m-2, p. 6-186, and pp. 6-107–18 for refractive indexes.

[6] J. H. Weaver, "Optical properties of metals," in *Handbook of Chemistry and Physics*, R. C. Weast, Ed., 67th ed. Boca Raton, FL: CRC Press, 1986/1987, pp. E377 et seq, Iron is found on p. E382.

[7] B. I. Miller, U. Koren, M. A. Newkirk, M. G. Young, R. M. Jopson, T. M. Derosier, and M. D. Chien, "Tensile-strained InGaAs/InGaAsP quantum-well optical amplifiers with a wide spectral gain region at 1.55 μm," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 520–522, May 1993.

[8] P. K. Tien, R. J. Martin, R. Wolfe, R. C. LeCraw, and S. L. Blank, "Switching and modulation of light in magneto-optic waveguides of garnet films," *Appl. Phys. Lett.*, vol. 21, pp. 394–339, Oct. 15, 1972.

[9] R. Wolfe, J. Hegarty, J. F. Dillon, Jr., L. C. Luther, G. K. Celler, L. E. Trimble, and C. S. Dorsey, "Thin film waveguide magneto-optic isolator," *Appl. Phys. Lett.*, vol. 46, pp. 817–819, May, 1985.

[10] M. Levy, R. M. Osgood, Jr., H. Hegde, F. J. Cadieu, R. Wolfe, and V. J. Fratello, "Integrated optical isolators with sputter-deposited thin-film magnets," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 903–905, July 1996.

[11] M. A. Newkirk, B. I. Miller, U. Koren, M. G. Young, M. Chien, R. M. Japson, and C. J. Burrus, "1.5 μm multiquantum-well semiconductor optical amplifier with tensile and compressively strained well for polarization-independent gain," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 406–408, Apr. 1993.

[12] K. Magari, M. Okamoto, and Y. Noguchi, "1.55 μm polarization-insensitive high gain tensile-strained-barrier MQW optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 998–1000, Nov. 1991.

[13] J. M. Hammer, J. H. Abeles, and D. J. Channin, "Polycrystalline-metal-ferromagnetic optical waveguide isolator (POWI)," final report, Ballistic Missile Defense Organization, Contract DASG60-95-0070, Jan. 31, 1996, pp. 5–7.

[14] J. B. D. Soole, C. Caneau, H. P. LeBlanc, N. C. Andreadakis, A. Rajhel, C. Youtsey, and I. Adesiday, "Suppression of modal birefringence in InP-InGaAsP waveguides through use of compensated tensile strain," *IEEE Photon. Technol. Lett.*, vol. 9. pp. 61–63, Jan. 1997.

[15] A. Ougazzaden and F. Devaux, "Strained InGaAsP/InGaAsP/InAsP multi-quantum well structure for polarization insensitive electroabsorption modulator with high power saturation," *Appl. Phys. Lett.*, vol. 69, pp. 4131–4132, Dec. 30, 1996.

[16] N. Yoshimoto, S. Kondo, Y. Noguchi, T. Yamasaka, and K. Wakita, "Polarization-insensitive field-induced refractive index change using a lattice-matched InGaAlAs/InAlAs multiple quantum well structure," *Appl. Phys. Lett.*, vol. 69, pp. 4239–4241, Dec. 1996.