# Complete magneto-optical waveguide mode conversion in $Cd_{1-x}Mn_xTe$ waveguide on GaAs substrate

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Complete magneto-optical mode conversion was attained in a waveguide of diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$ grown on GaAs substrate. Mode conversion ratio 98%±2% under a magnetic field of 5 kG was achieved in the waveguide with graded-refractive-index clad layer. The $Cd_{1-x}Mn_xTe$ waveguide showed an optical loss below 1 dB/cm, and a high magneto-optical figure-of-merit, 200 deg/dB/kG at $\lambda = 730$ nm. High efficiency magneto-optical mode conversion in a waveguide grown on a semiconductor substrate shows the feasibility of monolithical integration of an optical isolator with semiconductor optoelectronic devices.  [DOI: 10.1063/1.1644339]

Optical isolators and circulators are indispensable components for high-speed optical network systems. An isolator prevents unwanted oscillations in nonlinear circuits and stabilizes laser oscillation by preventing the backward traveling light from re-entering into the laser cavity. Circulators separate output and input ports in bidirectional data transmission systems. The isolator and circulator can only function by utilizing the inherent time-inversion asymmetric dielectric function of magneto-optical materials. In present optical networks, ferrimagnetic garnet oxide crystals such as $Y_3Fe_5O_{12}$ and $(GdBi)_3Fe_5O_{12}$ are used as magneto-optical materials for discreet optical isolators and circulators. Waveguide optical isolators based on these films have been reported.[1–5] Because most of the active optical elements (such as the laser diode, optical amplifier, modulator, and optical gate) are produced on GaAs or InP substrates, it is desirable to integrate monolithically all optical circuits on these types of substrate. However, garnet-film isolators and circulators have not been monolithically integrated with semiconductor optoelectronic devices, because these oxide crystals cannot be grown on semiconductor substrates. For realization of optical integrated circuits, integration of an optical isolator is one of the most difficult tasks. Several methods for integrating magneto-optical waveguide devices with semiconductor opto-electronics devices have been proposed. Yokoi *et al.*[6] and Levy *et al.*[7] proposed a direct bonding of a garnet waveguide onto a semiconductor substrate. Hammer *et al.*[8] and Zaets *et al.*[9] proposed hybrid structures of a semiconductor optical amplifier and a ferromagnetic metal films. In this letter we discuss another promising way of the integration, i.e., a magneto-optical waveguide made of diluted magnetic semiconductor.[10,11]

Diluted magnetic semiconductor $Cd_{1-x}Mn_xTe$[12,13] is promising as a magneto-optical material for integrated optical isolators and circulators. $Cd_{1-x}Mn_xTe$ shares the zinc-blende crystal structure with the typical semiconductor opto-electronic materials such as GaAs and InP; its film can be thus grown directly on GaAs and InP substrates. $Cd_{1-x}Mn_xTe$ also exhibits a huge Faraday effect (its Verdet constant is typically 50–200 deg/cm/kG)[14,15] near its absorption edge because of the anomalously strong exchange interaction between the *sp*-band electrons and the localized *d* electrons of $Mn^{2+}$. Furthermore, the tunability of its absorption edge from 1.56 to 2.1 eV with Mn concentration[12] makes the $Cd_{1-x}Mn_xTe$ magneto-optical waveguide compatible with AlGaInP:GaAs optoelectronic devices operating in the wavelength range of 600–800 nm. For longer-wavelength ($\lambda = 800$–$1600$ nm) optoelectronic devices, $Cd_{1-x-y}Mn_xHg_yTe$[16,17] can be used. Bulk optical isolators using these materials are now commercially available.[16] Magneto-optical conversion between TE and TM modes was demonstrated with a $Cd_{1-x}Mn_xTe$ waveguide grown on a GaAs substrate.[11] A TE–TM mode conversion ratio of 34% and magneto-optical figure-of-merit of 15 deg/dB/kG were achieved. For a practical integrated optical isolator, isolation ratio should exceed 20 dB and insertion loss should be below 1 dB. This performance can only be achieved with a magneto-optical waveguide having a mode conversion ratio above 95% and a figure-of-merit above 100 deg/dB.

TE–TM waveguide mode conversion ratio $R$ induced by the Faraday effect is expressed as a function of optical propagation length $L$ as[18]

$$R = \frac{\Theta_F^2}{\Theta_F^2 + (\Delta\beta/2)^2} \sin^2\left[\sqrt{\Theta_F^2 + (\Delta\beta/2)^2} L\right], \tag{1}$$

where $\Theta_F = V \cdot H$ is the Faraday rotation per unit length, $V$ is the Verdet constant, $H$ is the magnetic field strength, and $\Delta\beta$ is the difference in phase velocity (phase mismatch) between TE and TM modes. To increase mode conversion ratio, the Faraday rotation should be increased and the mode phase mismatch reduced. $Cd_{1-x}Mn_xTe$ is a paramagnetic material, so its Faraday rotation coefficient is linearly proportional to the applied magnetic field. However, we limit the magnetic field strength to 5 kG, which is a practical value obtained by permanent magnets. Also, in diluted magnetic semiconductors, Faraday rotation exponentially increases when the optical wavelength approaches the band gap.[14,15] However, for the wavelength near band gap the optical loss increases as

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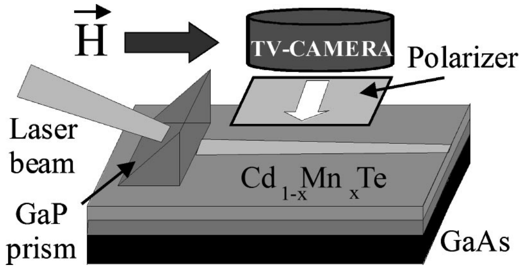


FIG. 1. Experimental setup to evaluate magneto-optical TE–TM waveguide mode conversion and optical propagation loss.

well and low optical loss is very important for an isolator. Another way to increase mode conversion ratio is to reduce TE–TM mode phase mismatch. If we consider a waveguide mode as a plane wave reflected between boundaries of a waveguide, the phase mismatch between TE and TM polarized modes exists due to the polarization dependence of the Fresnel reflection coefficient. It increases with increasing refractive index step at waveguide boundaries. At the boundary, if there is a graded change of refractive index through some thickness instead of a sharp step, the polarization dependence of the reflection coefficient should diminish. It is thus suggested that a graded-refractive-index layer at a waveguide boundary can reduce mode phase mismatch and enlarge magneto-optical mode conversion ratio. We studied the effect of the graded-refractive-index clad layer on magneto-optical properties of $Cd_{1-x}Mn_xTe$ waveguide.

$Cd_{1-x}Mn_xTe$ waveguide was grown with molecular beam epitaxy on GaAs (001) substrate.[19] It consists of a 3-$\mu$m-thick $Cd_{0.76}Mn_{0.24}Te$ waveguide cladding and a 1.2-$\mu$m-thick $Cd_{0.8}Mn_{0.2}Te$ waveguide core. The waveguide core was sandwiched between two 500-nm-thick $Cd_{1-x}Mn_xTe$ ($x=0.24$–$0.2$) graded-refractive-index clad layers, for which the Mn concentration was changed linearly with thickness. We used $Cd_{0.76}Mn_{0.24}Te$ layers as cladding layers, since GaAs is an optical absorber with a higher refractive index than that of $Cd_{1-x}Mn_xTe$, a single $Cd_{1-x}Mn_xTe$ layer on GaAs does not work as a waveguide.[10] One needs transparent cladding layers with smaller refractive index. $Cd_{0.76}Mn_{0.24}Te$ satisfies these conditions because $Cd_{1-x}Mn_xTe$ with higher Mn concentration has a smaller refractive index and wider optical band gap.[10–15]

Figure 1 illustrates the experimental setup for evaluating optical propagation loss and TE–TM waveguide mode conversion. A GaP prism was used to couple the laser light from tunable Ti:sapphire laser ($\lambda=680$–$800$ nm) into a $Cd_{1-x}Mn_xTe$ waveguide. A cooled charge coupled device television (TV)-camera collected light scattered normally from the film surface. A linear polarizer was placed in front of the TV camera with its polarization axis perpendicular to the light propagation direction. With this configuration, only the TE mode component of waveguiding light can be detected by the high-sensitivity TV camera. In the absence of a magnetic field, a scattered light streak was seen when the TE mode was excited [Fig. 2(a)], but it was not seen when TM mode was excited [Fig. 2(b)]. Also, weak dot-like scattering on defects was seen in both cases.

For the evaluation of the magneto-optical TE–TM waveguide mode conversion, a magnetic field was applied in parallel to the light propagation direction. A light streak with a periodically modulated intensity was observed for both TE mode excitation [Fig. 2(c)] and TM mode excitation [Fig. 2(d)]. Figures 2(e)–2(f) show the measured intensity of the modulated streak along the propagation length. The intensity was normalized to input intensity. The oscillations maximums in the case of TE excitation [Fig. 2(e)] correspond to the oscillations minimums in the case of TM excitation [Fig. 2(f)] and vice versa. Under an applied magnetic field the polarization of the waveguide mode rotates because of Faraday effect. If the TE–TM mode phase mismatch is not zero, the eigenmodes of the waveguide are elliptically polarized and the rotation between TE and TM polarizations is not complete.[11] As seen from Figs. 2(c)–2(f), the $Cd_{1-x}Mn_xTe$ waveguide with the graded-index-cladding layer shows almost complete mode conversion.

The surface of the fabricated waveguide was very smooth and it scattered light very weakly. That is the reason for the relatively large noise in the data shown in Figs. 2(e) and 2(f). However, the measured precision for mode conversion ratio, Faraday rotation, and mode phase mismatch was better than 2%, because both the period and amplitude of the mode conversion were fitted simultaneously for both cases of TE mode excitation and TM mode excitation. Figure 3 shows the TE–TM mode conversion ratio as a function of wavelength. The mode conversion has a maximum value of $98\% \pm 2\%$ at $\lambda=730$ nm. For the same waveguide without the graded-refractive-index clad layer the measured mode conversion ratio was only about 10%. Figure 4 shows the Faraday rotation and mode phase mismatch as a function of

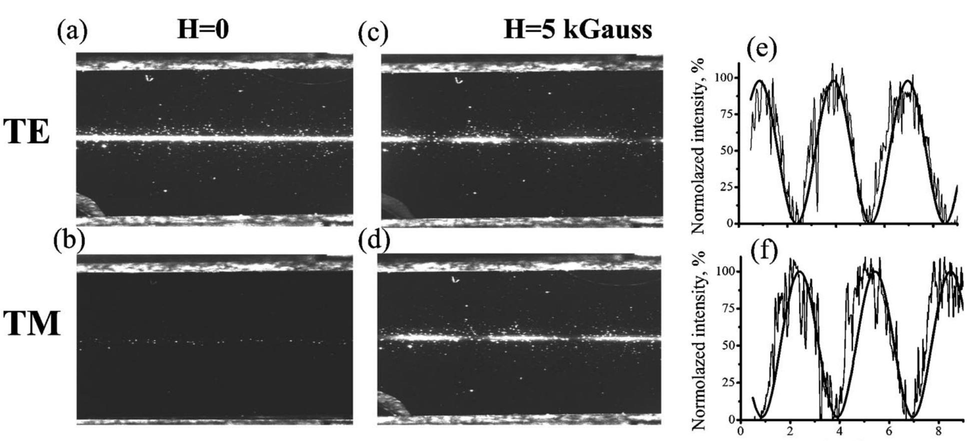


FIG. 2. TM–TE mode conversion ratio in $Cd_{1-x}Mn_xTe$ waveguide at $\lambda=730$ nm. Without applying magnetic field a light streak was observed (a) when TE mode was excited, but the light streak was not observed (b) when TM mode was excited. A spatially modulated light streak appears when magnetic field $H=5$ kG is applied in parallel to the light propagation direction for both (c) TE-polarized input and (d) TM-polarized input. Normalized intensity of light streak along propagation distance for TE-polarized input (e) and TM-polarized input (f).

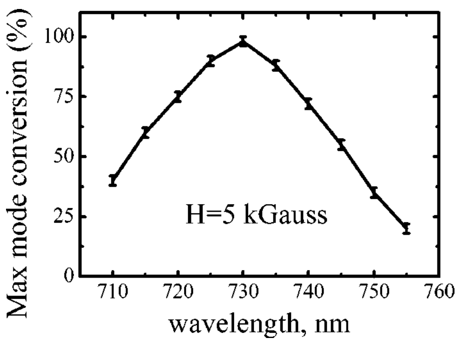


FIG. 3. TM–TE mode conversion ratio as a function of wavelength measured at $H=5$ kG.

wavelength. The Faraday rotation exponentially increases as wavelength approaches the band gap of the waveguide core layer. Such dependence is common for diluted magnetic semiconductors.[14,15] The mode mismatch has a minimum at $\lambda=730$ nm. For a given difference of Mn concentration between the core and cladding layers of the $Cd_{1-x}Mn_xTe$ waveguide, the difference between refractive indexes of the layers increases when light wavelength approaches the band gap.[10] That can explain the increase of the mode phase mismatch for $\lambda<730$ nm. On the other hand, the TE–TM mode phase mismatch generally becomes large for longer wavelength[20] as was observed for $\lambda>730$ nm.

Optical propagation loss was evaluated by an exponential fitting of the decay of the scattered light intensity as a function of the propagation length for TE-polarized input

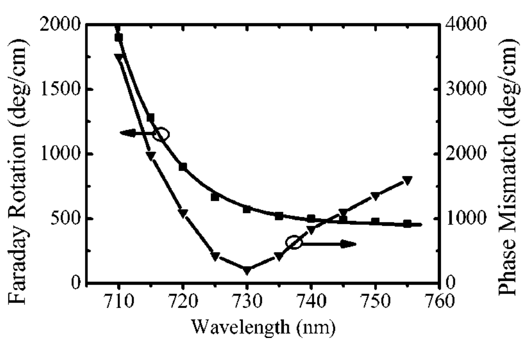


FIG. 4. Faraday rotation and mode phase mismatch as a function of wavelength measured at $H=5$ kG.

without an applied magnetic field [Fig. 2(a)]. Estimated optical loss of the waveguide mode was below 1 dB/cm at $\lambda=730$ nm. Such a small optical loss leads to the high magneto-optical figure-of-merit of 200 deg/dB/kG, which is sufficient for use in magneto-optical devices. We estimated numerically that a mode conversion of 98% is sufficient for fabrication of an optical isolator with an isolation higher than 25 dB.

In conclusion, graded-refractive-index $Cd_{1-x}Mn_xTe$ waveguide grown on GaAs substrate showed almost complete $98\%\pm2\%$ magneto-optical TE–TM mode conversion and a high magneto-optical figure-of-merit of 200 deg/dB/kG at $\lambda=730$ nm. It was found that graded refractive index layers are very effective to increase mode conversion ratio. This result is an important step to achieve a monolithic integration of optical isolators and circulators with other semiconductor-based optoelectronic devices.

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[1] K. Ando, T. Okoshi, and N. Koshizuka, Appl. Phys. Lett. **53**, 4 (1988).
[2] K. Ando, Proc. SPIE **1126**, 58 (1989).
[3] N. Sugimoto, H. Terui, A. Tate, Y. Katoh, Y. Yamada, A. Sugita, A. Shibukawa, and Y. Inoe, J. Lightwave Technol. **14**, 2537 (1996).
[4] R. Gerhardt, S. Sure, H. Doetsch, T. Linkewitz, and W. Tolksdorf, Opt. Commun. **102**, 31 (1991).
[5] T. Shintaku, Appl. Phys. Lett. **73**, 1946 (1998).
[6] H. Yokoi and T. Mizumoto, Electron. Lett. **33**, 1787 (1997).
[7] M. Levy, R. M. Osgood, A. Kumar, and H. Bakhru, Appl. Phys. Lett. **71**, 2617 (1997).
[8] J. M. Hammer, J. H. Abeles, and D. J. Channin, IEEE Photonics Technol. Lett. **9**, 631 (1997).
[9] W. Zaets and K. Ando, IEEE Photonics Technol. Lett. **11**, 1012 (1999).
[10] W. Zaets, K. Watanabe, and K. Ando, Appl. Phys. Lett. **70**, 2508 (1997).
[11] W. Zaets and K. Ando, Appl. Phys. Lett. **77**, 1593 (2000).
[12] J. K. Furdyna, J. Appl. Phys. **64**, R29 (1988).
[13] A. E. Turner, R. L. Gunshor, and S. Datta, Appl. Opt. **22**, 3152 (1983).
[14] S. Hugonnard-Bruyere, C. Buss, F. Vouilloz, R. Frey, and C. Flytzanis, Phys. Rev. B **50**, 2200 (1994).
[15] D. U. Bartholomew, J. K. Furdyna, and A. K. Ramdas, Phys. Rev. B **34**, 6943 (1986).
[16] K. Onodera, T. Masumoto, and M. Kimura, Electron. Lett. **30**, 1954 (1994).
[17] J. F. Dillon, J. K. Furdyna, U. Debska, and A. Mycielski, J. Appl. Phys. **67**, 4917 (1990).
[18] P. K. Tien, D. P. Schinke, and S. L. Blank, J. Appl. Phys. **45**, 3059 (1974).
[19] W. Zaets and K. Ando, J. Cryst. Growth **237–239**, 1554 (2002).
[20] T. Tamir, *Integrated Optics*, 2nd ed. (Springer, Berlin, 1979), pp. 19–54.