Periodically modulated ferromagnetic waveguide claddings with perpendicular magnetic anisotropy for enhanced mode conversion

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We present the results of a numerical study into mode conversion in an InP waveguide covered by an out-of-plane magnetized CoFe strip through the magneto-optical Kerr effect. We find that when the magnetisation direction in the strip is periodically switched along its length mode conversion is enhanced by a factor of 5 compared to a uniform magnetisation. We investigate the optical loss of ultrathin magnetic film claddings with perpendicular magnetic anisotropy and find that losses can be reduced by over a factor of two. The device envisioned could function as a mode converter that can be switched on and off by toggling the magnetic state. The non-reciprocal effects inherent in magneto-optics offer possibilities for optical isolator or circulator devices.

Introduction

In recent years the fields of photonic integration and nanomagnetism have independently taken huge strides. Recent discoveries in opto-magnetism and spintronics have provoked renewed interest in the investigation of so-called magnetic claddings for photonic waveguides. Magnetic materials have been investigated in the past as promising candidates in the search for integrated optical isolators [1]. In particular, the use of a ferromagnetic garnet thin film has been shown to induce a non-reciprocal phase shift [2], and ferromagnetic metals such as CoFe have been used to induce non-reciprocal optical losses [3]. The major drawback of such approaches are the large optical absorption in metallic claddings, as well as the problematic integration with waveguide material processing.

Here, we propose the use of ultrathin magnetic claddings with a perpendicular magnetic anisotropy (PMA) leading to an out-of-plane magnetisation. With the use of a PMA cladding on top of a photonic waveguide (a so-called ‘polar’ configuration), a mode propagating through the waveguide is converted between TE and TM due to the magneto-optical Kerr effect (MOKE) in the cladding. PMA films have been shown to exhibit relatively large magneto-optical effects while having the potential to minimize optical losses due to their ultrathin nature. Achieving significant mode conversion in such a relatively simple system could be useful in several photonic applications, but also has promising applications in the field of nanomagnetism as the reverse; the manipulation of the magnetic state by light in PMA films [4] is an emerging topic. Specifically, we propose using an arrangement where the magnetisation direction in the cladding periodically alternates to further enhance mode conversion.

In this proceeding we present 3D Finite-Difference Time-Domain (FDTD) simulation results of this system, as well as 2D Film Mode Matching (FMM) calculations to assess the optical losses of ultrathin PMA claddings.

3D FDTD simulations

We present 3D FDTD simulations of a system consisting of an InP waveguide (based on the IMOS platform [5]) cladded for a length of several microns by a 50 nm thick strip of an CoFe alloy. The dielectric tensor of this strip is chosen such that it represents an out-of-plane magnetisation ('up' or 'down' direction). Note that this setup is artificial, as such a strip would in reality have an in-plane magnetisation, and the system we simulate is purely used to demonstrate qualitative behaviour. We investigate two configurations of this system. Respectively, the uniform configuration, where the magnetisation of the strip is in the 'up' direction along its entire length, and the periodically modulated configuration, where the magnetisation in the strip is switched between 'up' and 'down' along its length with a period of 1.6 μm (related to the beating length of the modes in the waveguide, as will be explained later).

When the fundamental TE mode is coupled into this system, a partial conversion to the TM mode will occur in the region covered by the magnetic cladding.

In figure 1 we plot the TM/TE field ratio in both configurations as a function of the distance along the propagation direction. In the illustrations above the graph the region covered by the magnetic cladding is indicated for both the uniform and periodic configurations.

We find the maximum conversion from TE to TM to be 5 times higher in the periodically modulated system as compared to the uniform system. Significant mode beating is also visible due to the simultaneous propagation of both the TE and TM mode with different propagation constants. Note that edge effects are also visible at the end of the magnetic strip, distorting the oscillation. These are probably due to higher order non-propagating modes.

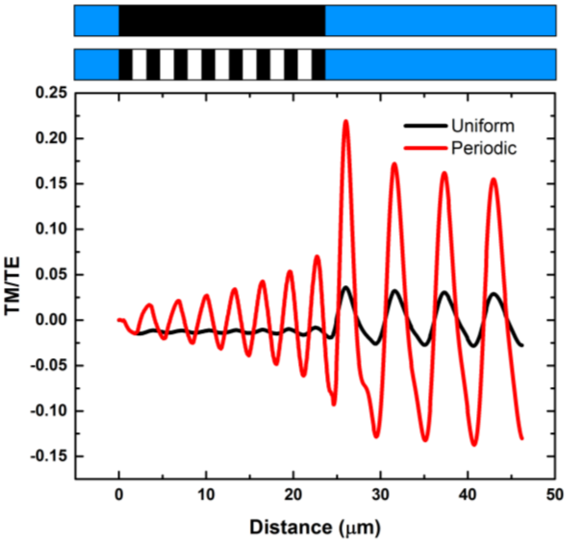

Figure 1. TM/TE field ratio as a function of distance along the propagation direction for a uniformly magnetized and a periodically modulated magnetic strip as indicated above the graph. The blue region indicates the bare waveguide, and the black and white regions indicate the strip with up and down magnetisation respectively.

To qualitatively understand this behaviour we use a set of rate equations, which describe the TE and TM modes as two coupled energy reservoirs. The magneto-optic interaction in the magnetic cladding facilitates conversion of energy from one reservoir to the other.

Furthermore, energy in both subsystems is lost over distance at different rates due to optical absorption, which is higher in the TM mode. In the limit where $TM/TE \ll 1$, as is the case when the initial mode is purely TE, we can reduce two coupled rate equations to one equation for TM/TE.

By plotting the real and imaginary part of the solution to this equation, we create a phase plot for the system as shown in figure 2a for the uniform magnetic configuration.

Starting from a purely TE mode ($TM/TE = 0$), conversion to the TM mode occurs in the magnetic cladding. At the same time, due to higher loss for the TM mode we observe an oscillation in the system, resulting in a sink to which the system always returns.

At the end of the cladding (transition from the blue to the red curve), mode conversion stops and the system again starts oscillating in phase space, now due to the difference in propagation constants for the two modes as is inherent for the used waveguide.
In figure 2b we show the same quantities resulting from the 3D FDTD simulation of the system.

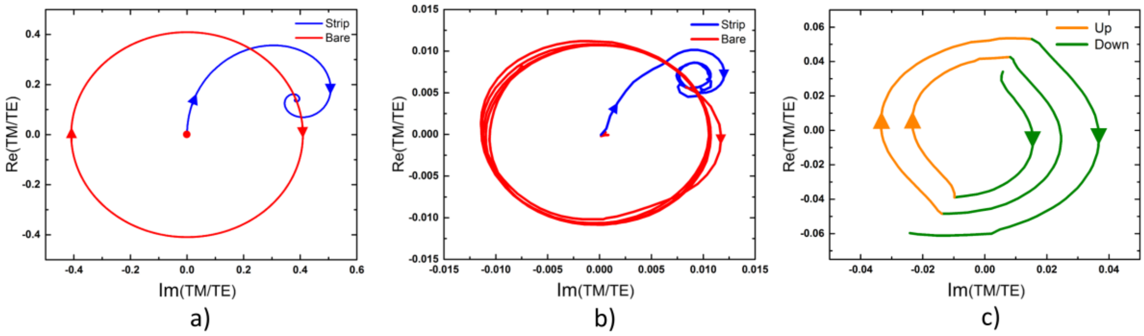

Figure 2. Phase plot of the real and imaginary part of the TM/TE field ratio in the uniform configuration as calculated from rate equations (a) and resulting from 3D FDTD simulations in the uniform (b) and periodic configuration (with up and down magnetization indicated) (c).

Here we see that the qualitative behaviour is reproduced well by the rate equation description for this limiting case. We can interpret this system as an oscillator, which helps us understand why mode conversion is enhanced when a periodic magnetisation configuration is used. In the uniform configuration, a constant 'impulse' is given to the oscillator, and a maximum amplitude is soon reached. In the periodic configuration we switch the magnetisation with the proper period, correlated with the beating length of the two modes, providing an impulse to the system in alternating directions in resonance, increasing the amplitude of the oscillator with each impulse, as can be seen in figure 2c. Note that the sink would still be at the same location if any of the sections were extended, we merely take advantage of the fact that the system relaxes to this sink in a different way.

Investigation of optical loss

One very important factor in this system is optical loss, as the absorption in metals is quite high, especially at telecom wavelengths. In the previous simulations we have used a 50 nm thick metal film, leading to a loss of 74 dB in a strip of 24 µm, or 3.1 dB/µm. For our approach this is not realistic, as actual PMA stacks are typically no thicker than a few nm. A typical PMA stack consists of at least three layers; an ultrathin magnetic material (~1 nm) e.g. Co(Fe) sandwiched between two non-magnetic heavy metal layers (2-4 nm), such as Pt or Pd, which harness a significant spin-orbit coupling, tilting the magnetisation out-of-the-plane and giving rise to the large polar-MOKE effect. Alternatively, the top metallic layer can be replaced by a dielectric such as Al_2O_3 or MgO to reduce the losses even further. The used heavy metals exhibit an extremely high optical absorption, so it is imperative to reduce the thickness of these layers as much as possible. In the following we assess the impact of our proposed material stacks.
Using a 2D FMM mode solver, estimates can be made of the optical absorption in waveguides cladded with PMA thin films.

We investigate the absorption as a function of the wavelength for two stacks, a 'standard' stack consisting of 1 nm of Co sandwiched between two 4 nm layers of Pt, and an optimized stack where the bottom Pt layer thickness is reduced to 2 nm and the top Pt layer is replaced by 4 nm of Al_2O_3, which has virtually no optical absorption. We calculate the insertion loss in waveguides covered with either of the stacks and find this to be 3.2 dB/μm in the standard stack, compared to 1.4 dB/μm in the optimized stack. This demonstrates the significant effect of the layer choice on the loss, even for these ultrathin layers. It is imperative to minimize the thickness of the non-magnetic layers or to choose more optimal materials. We already achieve a significant reduction in loss with this simple optimization, suggesting that even lower loss is achievable with further investigation.

Finally, it is also important to note that the high index heavy metal layers tend to pull more of the fields from the waveguide into the stack, increasing both the magneto-optical interaction as well as optical absorption. The complex interplay between these two effects, as well as the dependence of the magneto-optical properties on the surrounding layers, will be investigated in the future.

Conclusion & Outlook

In this work we have presented a device based on a periodic alternating magnetisation profile in a magnetic cladding with perpendicular magnetic anisotropy which has a 5 times higher mode conversion efficiency compared to a uniformly magnetized cladding. Furthermore, we show that the optical loss in these claddings can be reduced significantly by materials choice and reducing the layer thicknesses. Fabricating the device envisioned here is experimentally feasible, and our preliminary studies have shown that it is relatively straightforward to deposit PMA stacks on InP via magnetron sputter deposition. Using ion bombardment it is possible to locally change the magnetic anisotropy of the magnetic cladding, allowing for the realization of the periodically modulated magnetic strip with sub-micron resolution [6]. This would allow us to switch the magnetisation configuration between the uniform and periodic configurations, essentially creating a mode conversion device that can be toggled. Better control of the non-reciprocal effects could pave the way to integrated optical isolators and circulators using magnetic claddings.

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