All-optical modulator based on a ferrofluid core metal cladding waveguide chip*

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We propose a novel optical intensity modulator based on the combination of a symmetrical metal cladding optical waveguide (SMCW) and ferrofluid, where the ferrofluid is sealed in the waveguide to act as a guiding layer. The light matter interaction in the ferrofluid film leads to the formation of a regular nanoparticle pattern, which changes the phase match condition of the ultrahigh order modes in return. When two lasers are incident on the same spot of the waveguide chip, experiments illustrate all-optical modulation of one laser beam by adjusting the intensity of the other laser. A possible theoretical explanation may be due to the optical trapping and Soret effect since the phenomenon is considerable only when the control laser is effectively coupled into the waveguide.

Keywords: symmetrical metal cladding waveguide chip, ultrahigh order modes, ferrofluids, all-optical devices

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1. Introduction

With the rapid development of transformation optics and various nanophotonic devices,[1,2] the metallic planar waveguide has generated widespread interest specifically for its various advantages, such as simple structure, easy assembly, and the possibility of a negative refractive index.[1–4] A symmetrical metal cladding optical waveguide (SMCW) can excite ultrahigh-order modes in its millimeter scale guiding layer through free space coupling technology.[5] Compared with the extensively studied surface plasmon wave,[6] ultrahigh order modes are polarization-independent and can achieve deeper detection depth, higher sensitivity, and larger Goos–Hanchen shift.[7] In recent years, by using a symmetrical metal cladding optical waveguide chip, we have demonstrated a refractive index detection limit of 10^{-6} RIU (refractive index unit)[8] and observed the enhanced lateral shift of the reflected laser beam on the millimeter scale.[9] Furthermore, in the slow light area, the delay-bandwidth product of this waveguide chip is theoretically unlimited, and a slow light with a group velocity of only 0.017C is also illustrated.[10]

Ferrofluid is stable colloidal suspension of ultra-fine magnetic nanoparticles dispersed in either a polar or non-polar liquid. Such a fluid with magnetic properties has wide applications, particularly in the areas of aviation, medicine, and materials. In optics, the refractive index of ferrofluid relies on the external field, this feature can be utilized in various optical devices.[11] It is widely accepted that under an external magnetic field, chain-like or column-like nanoparticle clusters are formed along the direction of the magnetic field. Various tunable magneto-optic modulators based on the magnetic response to the ferrofluid have already been reported,[12–16] while no devices have been reported based on the light–matter interaction in the ferrofluid. In our previous work, the ferrofluids were sealed inside the sample cell of the symmetrical metal cladding waveguide chip to act as the guiding layer. Investigation shows that the switching speed of the ferrofluids under an external field is enhanced by three orders of magnitude, and a hypothesis is proposed that the nanoparticles self assemble into periodic pattern under the optical trapping effect of the excited guided modes.[17]

This work focuses on the interaction between the magnetic nanoparticle and the ultrahigh order modes under zero magnetic field. On the one hand, the regular distribution of nanoparticles relies on the optical field of the incident laser; on the other hand, the refractive index and absorption of the guiding layer can be tuned via adjusting the microstructure in the ferrofluids, which leads to a change in the phase match condition of the incident laser and finally results in a substantial variation in the intensity of the reflected beam. On these grounds, it is possible to design a small-size optical intensity modulator with good tunability in an all-optical manner.

2. Experiments and discussion

The schematic layout of the ferrofluid core metal cladding waveguide chip is illustrated in Fig. 1, where two gold films of 200-nm and 30-nm are deposited on the glass substrate and

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a thin glass film of 0.3-mm, respectively. The sample cell is a circular hole in a 0.7-mm-thick glass film, while the sample is pumped into the cell though the outlet and inlet. It is worthwhile to note that the parallelism between each interface of the structure is a crucial factor for the excitement of the ultrahigh order modes. The water-based Fe_3O_4 ferrofluid samples are provided by Anhui Jingke Magnetic Liquids Company, Ltd. The distribution of magnetic nanoparticle sizes ranges between 8 nm and 12 nm and follows the normal distribution, of which the central size is 10 nm. The mass densities of the ferrofluid and nanoparticle are 1.20 g/ml and 5.18 g/cm^3 respectively, and the mass of particles per volume fraction is 0.248 g/ml. In order to reduce the absorption of the guiding layer, the samples in the experiments are diluted to the volume fraction 0.032%. The whole waveguide can be divided into the following parts. The 30-nm thick gold film works as the upper coupling layer to enable the incident laser to directly couple into the guiding layer. The thin ferrofluid film in the sample cell acts as the guiding layer and the 200-nm thick gold film functions as the substrate to prevent light leakage from the bottom.

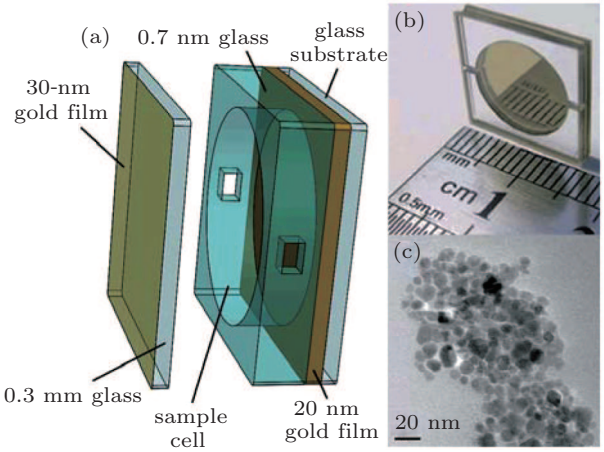


Fig. 1. (color online) (a) Schematic layout of the symmetrical metal cladding waveguide chip, (b) picture of the SMCW, and (c) magnetic fluid sample under transmission electron microscopy (TEM).

Ultrahigh order modes can be excited when the phase match condition is fulfilled. The originally reflected energy is lost from the reflected beam and transferred to the ultrahigh order mode; meanwhile, a resonance dip is formed in the reflection spectrum. Thus, the coupling coefficient can be tested via monitoring the reflected intensity. At the same time, the phase match condition is specified by the characteristics of the guiding layer, e.g., the thickness, the effective refractive index, and the absorption. The sensitivity of the ultrahigh order mode is so high that even a minor variation in the sample cell will drastically affect the detected reflectivity., We numerically calculate a 4-layer waveguide structure via a transfer matrix method with following parameters: the dielectric coefficient of the metal film and glass are $\varepsilon_{\text{metal}} = -17.3 + 0.68\text{i}$ and $\varepsilon_{\text{glass}} = 2.8$, the wavelength is $\lambda = 860$ nm, and the results are shown in Fig. 2. The dielectric coefficient of the sample is taken to be $\varepsilon_{\text{sample}} = \varepsilon_{\text{r}}$ for the line A, $\varepsilon_{\text{sample}} = \varepsilon_{\text{r}} + \Delta\varepsilon_{\text{r}}$ for the line B, $\varepsilon_{\text{sample}} = \varepsilon_{\text{r}} + \text{i}\Delta\varepsilon_{\text{i}}$ for the line c.

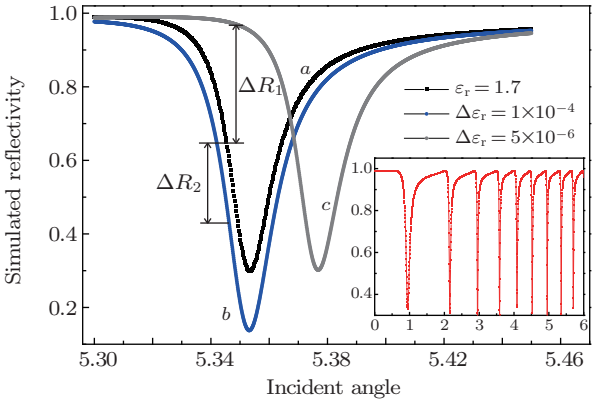


Fig. 2. (color online) Numerically simulated reflection spectra of the SMCW structure.

As the incident angle is relatively small, a series of sharp dips can be observed in the reflection spectrum with an FWHM (full width half maximum) smaller than 0.05 degree. Accordingly, higher sensitivity and better linearity can be achieved if the incident angle is fixed in the middle area of a rising or falling edge of a certain resonance dip. As can be seen in Fig. 2, when the real part of the sample dielectric coefficient changes a fold of 1×10^{-4}, or its imaginary part changes a fold of 5×10^{-6}, the corresponding variation in the reflection intensity can be observed obviously. Furthermore, it is clear that the real part of the dielectric coefficient determines the resonance positions, while the resonance width depends on the imaginary part. When the incident angle and wavelength of the laser are fixed, and other factors such as the slight vibration and temperature changing in the laboratory are trivial, the reflectivity relies mainly on the change of the sample characteristics, e.g., the distribution of the nanoparticles.

With no external field applied, the reflectivity variation is observed distinctly when we simply turn on and off the incident laser several times by using a shutter. The incident ansgle is fixed in the middle area of a falling edge, and figure 3 shows that the reflectivity corresponding to the moment of turning on the laser is always larger than before. Then, the reflectivity decreases gradually to a stable value in a few seconds. The longer the time when the laser is turned off, the larger the difference will be. The only possible explanation for the observed phenomenon is that the distributions of nanoparticles are different between with and without the light field, so are the effective refractive indexes of the guiding layer.

The power distribution along the vertical direction of the waveguide is a periodic function, which can be proved theoretically.[17] It is possible that the nanoparticles are confined in the high energy area by the optical trapping effect and

form a periodic density distribution, which is apparently different from the case when no optical field is applied. Further studies, such as by directly taking pictures of the microstructures, will be necessary to elucidate the details of the regular distribution of the nanoparticles under the excited ultrahigh order modes.

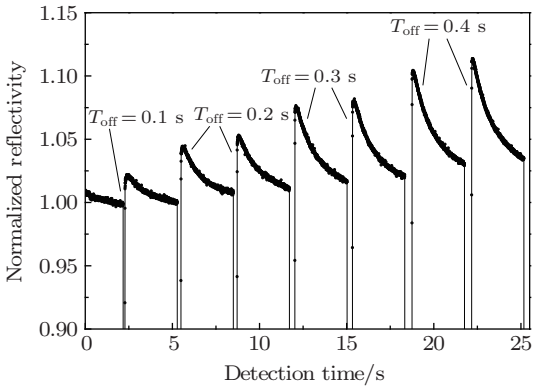


Fig. 3. Reflectivity variations as the laser is turned off/on several times.

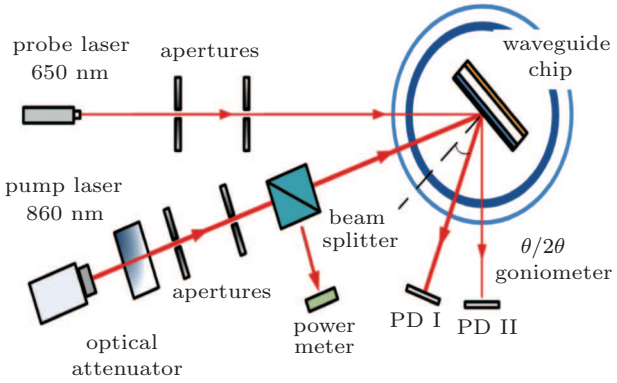


Fig. 4. (color online) Experimental setup for optical intensity modulation.

The experimental setup to carry out optical intensity modulation is illustrated in Fig. 4. Different from the previous experiments, the present experiment uses two lasers with different wavelengths and intensities. An 860-nm laser (DL100, Topical Photonics) with higher power works as the control laser and other 650-nm laser with lower intensity works as the detection laser. Two apertures are inserted into the paths of both lasers and a power meter (Coherent, Fieldmaster No. 33-0506) is used to monitor the power of the control laser. The waveguide chip and the photo–diode (PD) are fixed on a $\theta/2\theta$ goniometer, which is used to carry out angular scanning assisted by a computer. Since the control laser power is much larger than the detection laser power, the light–matter interaction induced by the detection laser can be neglected. The proposed all-optical modulator works as follows: the control laser is coupled into the guiding layer via free space coupling technology and excites a single ultrahigh order mode in the ferrofluid, which redistributes the nanoparticles into regular pattern. Through adjusting the intensity of the control laser, the effective refractive index of the guiding layer varies, and consequently, modulates the reflectivity of the detection laser. To verify the above mechanism, we tune the control laser power at different incident angles, and the reflectivity of the detection laser is recorded when the value becomes stable. The control lasers at incident angles $\theta = 12.5°$, 21°, and 29° correspond to the bottoms of the resonance dips, where most laser power is coupled into the guiding layer. The parts corresponding to incident angles $\theta = 8.5°$ and 16.5° are at the top of the resonances, which means that the coupling coefficient is extremely low. The incident angle of the detection laser is fixed in the middle of rising edge of a resonance dip to obtain high linearity. It needs to be mentioned here that an opposite phenomenon can be observed when the detection laser is fixed in the middle of falling edge. Figure 5 demonstrates the detected reflectivity of the detection laser, which is normalized to the value when the pump laser intensity is zero.

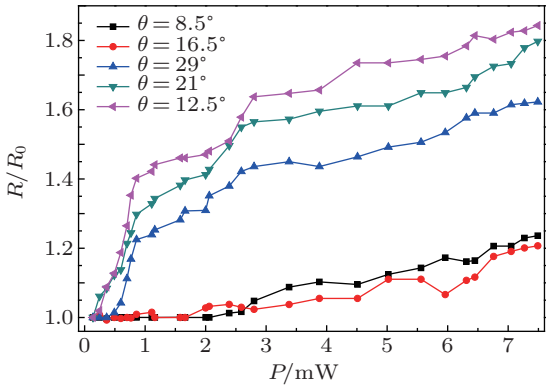


Fig. 5. (color online) Detection laser reflectivities versus control laser intensity at different incident angles.

Experimental results show that when the control laser is effectively coupled into the waveguide, i.e., an ultrahigh order mode with high field density is excited, there is an abrupt increase in the reflectivity of the detection laser, followed by a slow growth. This is different from the cases where the control laser is under the weak-coupling condition and no apparent reflectivity variations can be observed as the control laser intensity increases continuously. The experiments confirm that the ultrahigh order mode excitement is a necessary condition to realize all-optical modulation. In addition, the local temperature at the incident spot increases with the control laser intensity increasing, and the nanoparticles will escape from those "hot" regions to the "cooler" parts according to the Soret effect.[18] This may explain why all the curves show an increase trend. Clearly, the physics behind the abrupt increase is quite different from that behind the slow growth, and a tentative explaination can be established based on the optical trapping effect and the Soret effect. In our experiments, the nanoparticles tend to distribute regularly under the optical trapping effect, and this results in the observed abrupt increase. On the other side, the

Soret effect, which varies the local volume fraction of the ferrofluids at the incident spot, leads to a much slower variation.

3. Conclusion

Based on a symmetrical metal cladding waveguide structure and ferrofluids, this paper demonstrates an optical intensity modulator, where the reflectivity of one laser can be modulated by another laser through adjusting the microstructure of nanoparticles in the guiding layer. It is suggested that the nanoparticles of the ferrofluid are distributed regularly under the excited ultrahigh order mode pattern due to the optical trapping effect, which leads to an abrupt variation. The temperature difference induced diffusion may also result in a slow variation.

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