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# Fully Integrated Magneto Optic in Fiber Micro Modulator

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## Abstract

In this paper we present the construction and the preliminary testing of an integrated magneto optic in-fiber modulator. The modulation concept is based upon insertion of Fe micro particles into holes drilled in an optical single mode fiber reaching the fiber's core, and spatial translation of the particle in the hole, by means of external alternating magnetic field. Preliminary results show an extinction ratio of about -4dB.

**Keywords:** Magneto optics; Micro Fe particles; Optical fibers

## Introduction

Construction of in-fiber modulator has high importance in optics communication. In this paper we present the first step towards the development of a fully integrated optical modulator based upon insertion of magnetic Fe micro particle inside a single mode fiber (SMF). Shifting the particle will enable creating modulation over the optical signal going through the core of the fiber. The main advantages of this device are by having both high operation rates (theoretically can exceed a few GHz) as well as being integrated with optics communications modules. One important application for using such a modulator for Q switched laser as the temporal width of the Q switched pulse inversely dependent to the length of the modulator. In this case the modulator is very small (overall length of less than few tens of microns) which may allow in the future the realization of ultra-short pulses in Q switched lasers. One example for that is using saturable absorber in graphene [1] or using a few-layer Molybdenum Disulfide (MoS2) saturable absorber [2].

Several methods have been employed to produce magneto optic modulator using magnetic fluid as a cladding layer where the refractive index of the cladding is changed by applying external magnetic fields [3,4]. Other concepts include magneto optical modulator which is based on Faraday rotation effect [5,6] or manipulation of magnetic micro-beads in suspension [7].

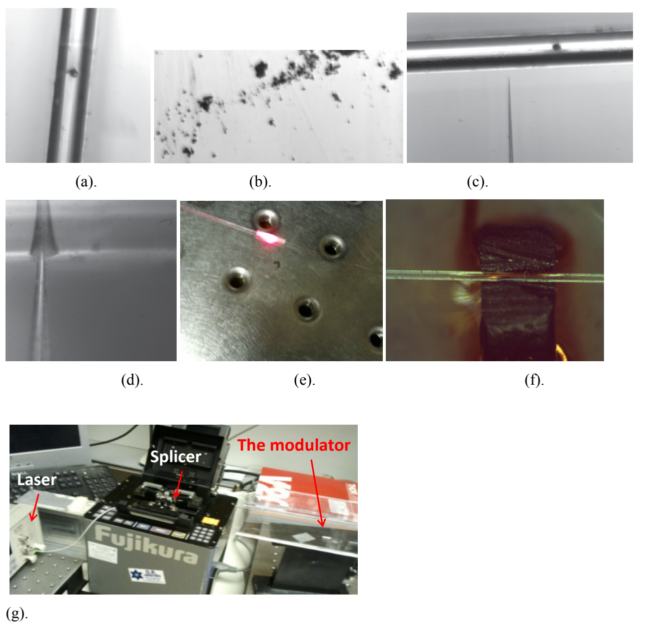


**Figure 1:** Modulator fabrication steps. (a). Drilling the holes. (b). Image of the micro particles. (c). Insertion of the tip near the drilled fiber. (d). Insertion of the particles into the hole. (e). The constructed fiber. (f). The fiber in the magnet. (g). The experimental setup.

The operation concept of the proposed modulator was demonstrated before by the authors [8] but a fully integrated modulator was never constructed before. The modulator includes drilling of micro scale hole in a single mode fiber. The hole is passing through the core of the fiber. Then, we insert a micro size Fe particle into the hole. By applying external magnetic field i.e. by connecting current to a wire that will be wired around the fiber as part of a solenoid, the Fe particle will be shifted within the hole due to the applied external magnetic fields. When the particle is shifted into the optical core of the fiber it scatters the light and no light goes through. When the external magnetic field shifts the particle away from the core, most of the light is able to pass through the core of the SMF.

The advantages of this concept are the small size of the modulator (a few tens of microns), the fact that it can be easily integrated into any optical system that includes fibers, without the need of prior fabrication, polarization independence, and modulation bandwidth of the full optical spectrum.

In this paper we describe the fabrication, integration and preliminary testing of such an integrated micro modulator.

## The Modulator Fabrication and Testing

The first part involved drilling the hole. The drilling was done by Altechnica from Lithuania. The holes were required to be 20-30 μm in diameter, and about 70 μm deep, so that the hole just penetrated the fiber core. The hole could be located using an optical microscope at moderate magnification (X10 - X40). The top view of the drilled hole can be seen in Figure 1a. The second step was getting the iron microparticles (3-5 μm diameter). The particles were purchased from Polysciences, USA. It was a metallic ion powder. In Figure 1b we show

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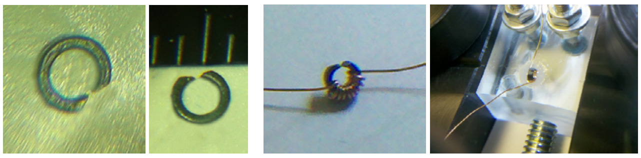
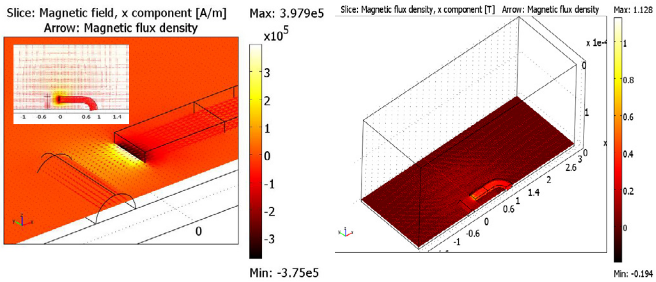


(a). (b).

**Figure 2:** (a). The Ferrite ring. (b). The construction of the magnetic modulator unit.




(a). (b).

**Figure 3:** Numerical simulation of the generated magnetic field and flux for the proposed configuration. (a). The magnetic field *H* in units of A/m with a cross section inset. The distance units are in 0.1mm (every 1 equals 100 μm). (b). The magnetic flux *B* in units of Tesla.

a picture of a microscope view of numerous powder micro-particles on a glass slide. The next step was building an integrated set-up for examination of the drilled fibers and manipulation of micro-particles. We have built a set-up which enables viewing of the fiber, positioning and rotation under the microscope. For manipulation of micro-particles we have used a "Micro-pipette Puller" (MDI instruments) to form a glass rod tapered down to approximately 3 μm which can push, and even lift, the micro-particles (Figure 1c).

The next step was the insertion of the particles into the drilled hole. In order to insert the Fe particles into the hole, we used the micropipette tip and relied on the natural adhesive power existing between the glass tip and the 3-4 μm Fe particles. We inserted the tip with few particles attached to it in to the fiber from the side as shown in Figure 1d. The insertion concept was successful provided that a large enough amount of particles are attached to the tip so that statistically there is a bigger chance for some particles to remain in the fiber and that the adhesive powers are weaker for the particles in the periphery making it easier to leave the tip. Once the particles are within the hole, they can be seen in microscope (we used X40 magnification). After the insertion we used a ceramic ferule (used normally for connectors) to cover the hole region. The tight diameter of the ferule which was only 128 μm (only 3 μm bigger from the fibers diameter) is crucial in order to block the hole entrance and prevent the particles from escaping the hole in the modulation process. The tightness of the ferule ensures the remaining of the ferule around the hole, even without gluing. In the picture of Figure 1e we can perceive some optical losses of a red laser beam from the hole within the ferule. Because of the tightness of the ferule around the fiber, the process of puling the ferule to the hole region should be done with great care, because of the fragility of the fiber-especially in the hole region.

The next stage was to splice the fiber to a FC/PC connector, couple one end to a laser (we used a laser source at wavelength of 1557 nm), the other end to a multimeter and to place the hole region under strong alternating magnetic fields (Figure 1f).

## Magnetic Modulation Unit

The magnetic modulation device capable of producing high magnetic fields around a V-groove into which a fiber is to be inserted was generated. Ferrite ring was coated using diamond coated dental instrument. Magnetic permeability of ring is about 20,000. It has external diameter of 2.5 mm, internal diameter of 1.7 mm and thickness of 1 mm.

Coil of 9 turns was made by wire of 0.1 mm (see left side of Figure 2a). Ferrite ring was adjusted on linear slider by epoxy adhesive. Contact screws were made for current connection to the coil. In the picture of the right side of Figure 2a, one can see two V-groves (on a black material from left and from right near the linear slider). The V-grooves are needed for the experimental optical fiber adjustment. In Figure 2b one may see the full construction of the electro-magnetic fiber modulator while in the left side of Figure 2b one may see the coil with the solenoid and in the right side the full electro-magnetic fiber modulator.

## Results

We started by performing some simulations for the possible magnetic field that can be generated by the proposed magnetic modulator. In the image of Figure 3 we present some numerical simulations for the strength of the magnetic field and flux that can be generated by the proposed modulator. In the figures one may see the Fe particle (left side) and the probe of the solenoid (the edge of the ferrite arriving to the V groove where the fiber is). In Figure 3a we show the magnetic field *H* and one may see that we reach the field strength of around 0.3M A/m and in Figure 3b we show the magnetic flux *B* and the strength there reaches the value of around 0.3 T. In Figure 3a one may see an inset being the cross section of the obtained magnetic fields. The distance between the particle and the probe in our simulation was around 50 μm. Note that *B* is proportional to $\mu_0 H$ and the gradient of *B* is proportional to the obtained magnetic force.

Note also that

$$H = \frac{N}{L} i \qquad (1)$$

While *i* is the current, *N* the number of loops of a solenoid and *L* is its length. To obtain magnetic field of $3\times10^5$ [A/m] for wires having width of 1μm (i.e. $N/L=10^6$) we will require a current of $i$=0.3[A] which is a feasible current for those type of wires and it may be obtained without melting the wires.

Note that the translation between the magnetic flux *B* and $F_M$ which is the magnetic force applied on the magnetic micro particle can be evaluated as:

$$F_M = \nabla\left(VM \cdot B\right) \qquad (2)$$

where *V* is the volume of the Fe micro particle and *M* is its magnetization which can be around *M*=1,000,000 [A/m]. ∇ is the spatial gradient.

After the simulations we performed some preliminary experimental validation using the constructed above mentioned integrated prototype. The optical modulation obtained was from maximum output intensity of 66 μW to 26 μW (about -4dB of extinction ratio). It seems that the adhesive powers between the particles and the fiber walls are strong and a coating that will reduce the adhesion forces in the hole should

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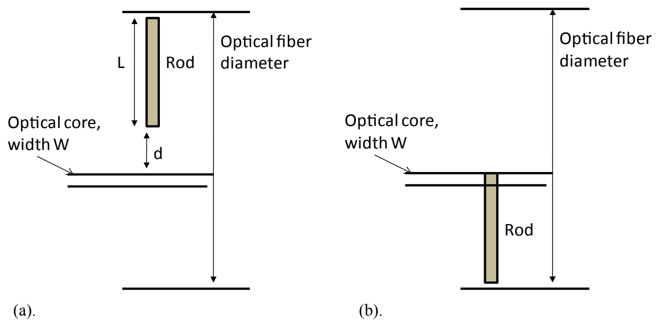


**Figure 4:** Schematic sketch for using of micro rod rather than a micro sphere. (a). Position of the rod in its upper state. (b). Position of the rod in its lower state.

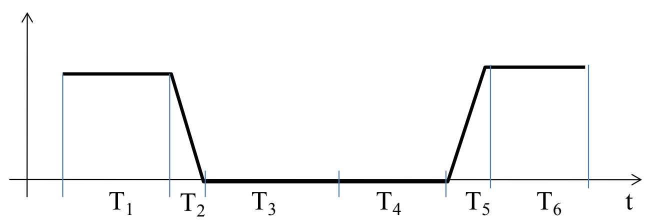


**Figure 5:** Schematic sketch of the timing diagram.

be considered in the next version of prototype based upon the current concept.

## Response Time Enhancement

In the applications involving the generation of ultra-short Q switched laser pulses in many cases it is much more important to have ultra-fast response time (rise and fall time) of the modulator rather than the operation frequency. This means that in some applications the modulator can operate at low frequencies but have fast rise/fall time of its modulated pulses. One interesting approach that may allow significantly reducing the response times while only very small magnetic force are needed, is described below. Let us observe the schematic sketch presented in Figure 4.

In this approach we will use micro rods rather than spherical Fe micro particles. The idea is to allow the micro rod to accelerate such that even if small forces are applied it can reach high velocities which will cause the generation of short modulation rise/fall time. Turning off of the light through the core:

$$T_1 = \sqrt{\frac{2d}{a}} \tag{3}$$

Where the distance *d* appears in Figure 4 and *a* is the acceleration. The time slot notations can be seen in Figure 5.

The acceleration *a* equals to:

$$a = \frac{F_M}{\rho LA} \tag{4}$$

With $F_M$ being the applied magnetic force, *A* the cross section area of the rod and *L* is its length. $\rho$ is the density of the rod. Assuming it is made out of Fe and then $\rho$=7860[kg/m$^3$]. Assuming also that $A$=10$^{-14}$[m$^2$], $W$=8[μm] and $F_M$=25[μN] (magnetic force generated at relatively low magnetic fields). We will assume that for the simplicity of modeling, the rod is moving in a vacuum generated at the drilled hole inside the fiber.

The time until the edge of the rod reaches the optical core equals to:

$$T_2 = \sqrt{{T_1}^2 + \frac{2W}{a}} - T_1 \tag{5}$$

Time until the rod passed across the optical core and shuts the light passing through off. $T_2$ is the fall time.

$$T_3 = \sqrt{(T_1 + T_2)^2 + \frac{2(L-W)}{a}} - (T_1 + T_2) \tag{6}$$

Turning on of the light going through the core:

$$T_4 = \sqrt{\frac{2(L-W)}{a}} \tag{7}$$

Time until the lower edge of the rod reaches the optical core.

$$T_5 = \sqrt{{T_4}^2 + \frac{2W}{a}} - T_4 \tag{8}$$

Time until the lower edge of the core passes through the optical core. This is the rise time.

$$T_6 = \sqrt{(T_4 + T_5)^2 + \frac{2d}{a}} - (T_4 + T_5) \tag{9}$$

Note that the maximal operation frequency is relatively low and it equals to:

$$\nu = 1 \Big/ (T_1 + T_2 + T_3 + T_4 + T_5 + T_6) \tag{10}$$

From the equations above we obtain that when choosing L=33 μm, d=27 μm (L+d for SMF should be around 60 μm): $T_2$=$T_5$=10[nsec], 1/ν=223[nsec]. This means that although the operation frequency will be limited to few MHz, the response rise/fall time is in the range of few nsec.

## Conclusions

Although only preliminary outcome was obtained, in this paper we present the procedure for the construction of a fully integrated magneto optic fiber modulator based upon Fe micro particles whose controlled movement performs the modulation on the light passing through the core of the optical fiber. The proposed concept realizes a micro metric optical modulator that due to its small dimensions can be very useful for generation of ultra-short active Q switched lasers. The paper also contains a proposal of how to significantly reduce the fall/rise time of modulation even when small magnetic fields are used.

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