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Abstract

The utilization of a bismuth-substituted iron garnet as a magnetooptic Faraday rotator (MOFR) has been reported for all-optical networking purposes as well as for other applications. Our measurements and observations demonstrate that the MOFR saturates once a significantly large magnetic field (>225 G) is applied. After the applied magnetic field enters the saturation region, the material's magnetic domains can become pinned at intermediate levels of magnetization. Pinning in this form has not been reported nor well studied for this application. In this paper, a method to detect and describe anomalous pinning in terms of Faraday rotation is presented. Measurements on the changes in the state of polarization that a pinned material produces are examined. This paper will also present practical methods for unpinning the MOFR material, which are traditionally considered to be challenging.

Keywords

Bi-substituted iron garnet, domain pinning, Faraday rotation, partial saturation

Disciplines

Controls and Control Theory | Signal Processing | Systems and Communications | VLSI and Circuits, Embedded and Hardware Systems

Comments

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Interferometric Detection of Pinned Interactions in Bismuth-Substituted Iron Garnet

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The utilization of a bismuth-substituted iron garnet as a magnetooptic Faraday rotator (MOFR) has been reported for alloptical networking purposes as well as for other applications. Our measurements and observations demonstrate that the MOFR saturates once a significantly large magnetic field (>225 G) is applied. After the applied magnetic field enters the saturation region, the material's magnetic domains can become pinned at intermediate levels of magnetization. Pinning in this form has not been reported nor well studied for this application. In this paper, a method to detect and describe anomalous pinning in terms of Faraday rotation is presented. Measurements on the changes in the state of polarization that a pinned material produces are examined. This paper will also present practical methods for unpinning the MOFR material, which are traditionally considered to be challenging.

***Index Terms*—Bi-substituted iron garnet, domain pinning, Faraday rotation, partial saturation.**

I. Introduction

MAGNETOOPTIC Faraday rotators (MOFRs) have been reported to be used in optical switching systems as well as in other applications [1]–[5]. Large magnetic fields (≈100–500 G) are typically applied to these MOFR materials to initiate Faraday rotation [6]. Often, when the magnetic field is well above saturation (225–335 G), or if the magnetic field is applied for long durations (Typically 10–20 μs or more), it is observed that MOFR materials become pinned in particular orientations of magnetization [6], [7]. The pinned state makes the MOFR unresponsive to further magnetic field variations. When a saturating magnetic field is applied to the MOFR material for a long duration, it causes the material's domains to become pinned at that level of magnetization, rendering the MOFR unresponsive and ineffective for magnetooptic switching applications. To regain the MOFR's utility, or to unpin the material, a controlled reduction in the applied field must be executed, allowing the domains to revert back to their original thermodynamically stable orientations.

In this paper, experimental demonstrations of pinning and unpinning of a Bi-substituted iron garnet as used in prior work [1], [2] will be presented. Furthermore, characteristics of a pinned material will be identified. The MOFR will be considered to be in a pinned state when despite changes in the applied saturating field, the MOFR will retain its magnetization. The existence of such states will be verified via Faraday rotations observed with/without an externally applied magnetic field.

II. Experimental Setup and Process

The MOFR used in these experiments was a Bi-substituted iron garnet (saturating field 225 G) grown in the 111 direction, a popular material used for magnetooptic switching applications [8]–[14]. A Sagnac interferometer configuration (Fig. 1), as described in the prior work [1], [2], was used in order to

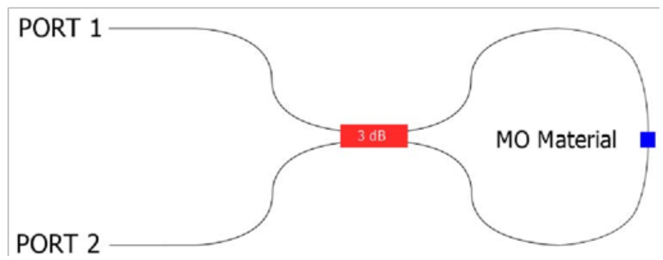


Fig. 1. Fiber-optic Sagnac interferometer [1] used to observe pinned and unpinned domains in MOFR.

observe changes in optical response when the material was pinned and unpinned. Faraday rotation was achieved using a pulsed magnetic field of intensity 125 G with a pulsewidth in the range of 1 μs. This pulsed magnetic field profile does not saturate the MOFR and results in an expected optical output at PORT 2 of the Sagnac interferometer. The optical output of PORT 2 was measured using a photodetector connected to an oscilloscope.

The MOFR was consequently driven into a saturated state by quickly increasing the applied pulsewidth and amplitude to 10–20 μs and 225–335 G, respectively, and quickly reducing the pulsed magnetic field to its normal operating conditions (1 μs, 125 G). Presence of pinned domains was identified when, after quickly modifying the applied magnetic field as described, the expected optical response was no longer produced. Consequently, at this state, the magnetic pulse no longer produces an optical response when the same applied magnetic pulse was previously able to create an optical response.

There are several methods for unpinning the MOFR. In our experiment, the MOFR was unpinned by briefly applying a magnetic field with the same or greater intensity than the one that originally pinned it. The field intensity could be controlled by decreasing both the amplitude of the pulse and the pulsewidth. Another method to unpin the material was to use a combination of magnetic pulses, and the application of a physically moving dc magnetic field. Unpinning may also be accomplished by physically moving a dc magnetic field close to the material for a short period of time, and then

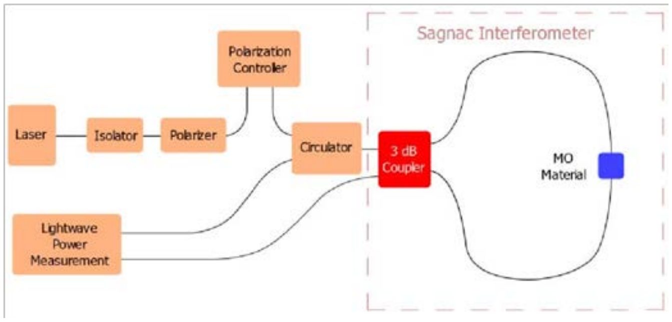


Fig. 2. This setup was used to measure the Faraday rotation of the MOFR material. The polarization controller is essential to ensuring the state of material. The polarization does not affect the polarization-dependent power measurements.

removing the applied magnetic field. The dc magnetic field was applied using a permanent magnet. For the purpose of this paper, the material can be considered to be in an unpinned state when an applied magnetic field begins to produce a response. The optical system (Fig. 2) used to measure the Faraday rotation of the MOFR was set up as follows. A laser set to 1550 nm was connected to a polarizer and sent into a polarization controller. The polarization controller was connected to a circulator. The circulator was used to measure the output of PORT 1 of the Sagnac interferometer. Both the ports of the Sagnac interferometer were connected to an optical power meter to measure the power output. PORT 1 was connected through the circulator and PORT 2 was measured directly (illustrated in Fig. 2). While the material was placed within the Sagnac loop, the laser input was sent through a polarization controller.

Since the optical system is not polarization maintaining, the output power will be sensitive to different levels of polarization. To ensure that this does not affect the measurement of Faraday rotation, the polarization controller can be used to take measurements at each of the different states of polarization. In our experiment, the polarization angle, ϑ, was varied from 0° to 360° with measurements at each degree.

To avoid environmental disturbances, multiple power measurements were taken for each degree of polarization, and then the measurements were averaged. The power measurements recorded from these polarization sweeps were curve fitted to $\cos^2(\vartheta)$ to determine the precise location of the maximum power. On comparing the location of the maximum output levels of the pinned and unpinned materials in the polarization sweep, we can determine the effect of the MOFR material on the state of polarization. Table I shows how different levels of Faraday rotation will affect the power measurements.

III. Discussion

When the MOFR material is pinned, it no longer responds to nonsaturating applied magnetic fields. A possible explanation for this observation is that magnetic domains within the material are pinned in localized directions which may be offset only on application of larger magnetic fields (above 225 G). It is hypothesized that this domain pinning is occurring due to domain walls becoming stuck on material defects, as has been reported on more localized scales in many magnetic

TABLE I

Sagnac Interferometer Response to Varying Degrees of Faraday Rotation Exhibited by the MOFR

Faraday Rotation	Normalized Output Power in Port 1	Normalized Output Power in Port 2
0 Degrees	1	0
45 Degrees	0.5	0.5
90 Degrees	0	1

materials [7]. The quickly changing applied magnetic field may be forcing domain walls to wrap around defects in such a way that the removal of the magnetic field does not allow the domains to completely reorient back into their original states. However, further research in this direction is necessary.

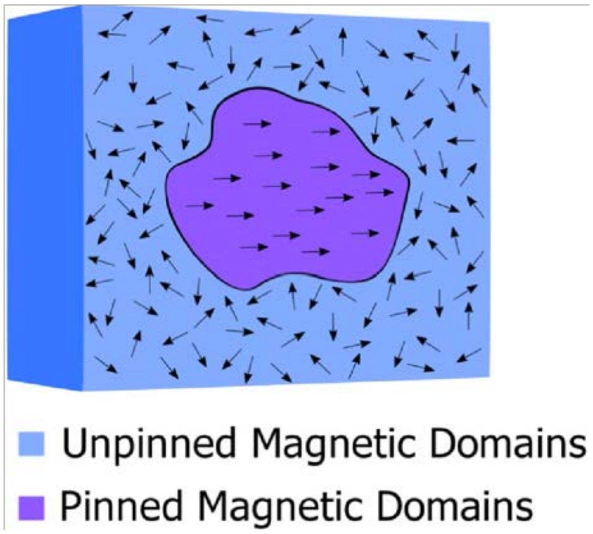
A. Pinned and Unpinned MOFR Materials

The application of a pulsed magnetic field to the MOFR material causes Faraday rotation to occur. This change in rotation creates an optical pulse that can be measured using an oscilloscope. The observed optical pulse is a measurement of how the material responds to an applied magnetic field. If the same optical pulse occurs when a magnetic pulse is reapplied, then the material is not pinned. If a longer magnetic pulse with a larger magnitude is applied for an excessive period (60–120 s), the pinned domains will form in the material, and no optical pulse will be observed. Pinning is observed to occur when a saturating magnetic field is applied to the material for an excessive time period.

It should be noted that our experiments show that pinning is not immediate. There is also a noticeable intermediary period in which the material produces a different optical pulse even when the same magnetic pulse is applied. The material seems to continuously change how it responds to the applied magnetic pulse when a pinning magnetic field is applied for a short period of time. This is expected due to the variations in the internal magnetic domain movement and alignment. Sometimes the optical pulse may even become negative, indicating that the Faraday rotation is acting in the opposite direction than it did initially. If the magnetic pulse is quickly moved back from the intermediary range to a nonpinning range, then the optical pulse will stop changing. However, the optical pulse may be different from what it was originally. If the pinning magnetic pulse is applied for too long, the optical pulse will disappear. When the optical pulse disappears, it means that the material is no longer responding to the magnetic pulse that originally produced a response. This is how the material becomes pinned.

B. Partially Pinned MOFR Material

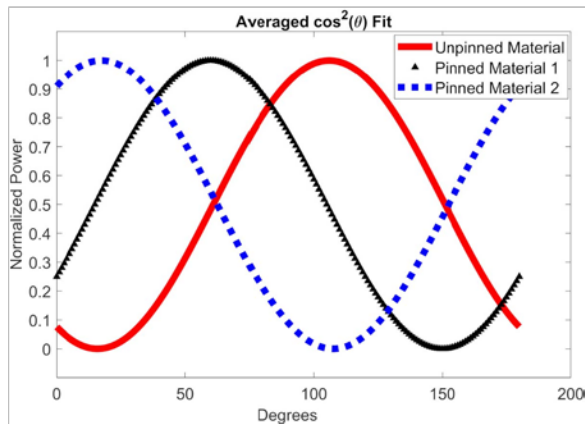
There seems to be a state between the material's pinned state and the material's normal operation, where it becomes partially pinned (Fig. 3). In this state, the optical pulse changes from its expected response. If the material is partially pinned, then some of the domains will not move when the magnetic pulse is applied, and the optical pulse will appear to be



unpinned regions (Fig. 3) can cause different optical states to be observed even when no field is applied.

In order to unpin the material, it must be slowly demagnetized. The material can be unpinned by briefly applying a slightly larger or longer magnetic pulse than the one originally used to pin it, then shortening the magnetic pulsewidth until the optical pulse reappears. However, this method is difficult to do, as it can easily pin the material at a higher level of magnetization. An easier method is to use a magnetic pulse that is below the level that the material was originally pinned at, and then physically move a magnet back and forth near the material. Various experiments of this method verified that this movement helps the domains move back into an unpinned state.

Fig. 5. Unpinned material was pinned at different places on the hysteresis. The pinning in these materials resulted in a phase shift of −46° and −90°, respectively. This can be seen by referencing the maximum power of the pinned



materials to the maximum power of the unpinned material.

Fig. 3. In a partially pinned material, some of the domains will be pinned into place, whereas other domains will still be able to react to an applied magnetic pulse. If too many of the domains are pinned, the unpinned domains will not be able to respond to an applied magnetic pulse.

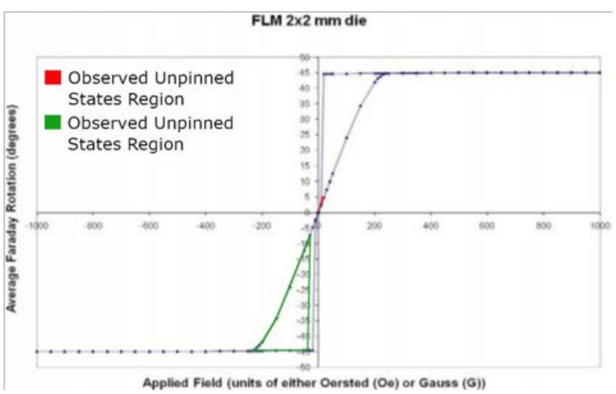


Fig. 4. This figure shows where different pinned states were pinned on the hysteresis of the material. Even some unpinned states showed some minor pinning. The reason for this is that the unpinning process does not ensure that the material becomes completely unpinned. Adapted figure courtesy integrated photonics now part of II–VI Incorporated [15].

modified from its original state. Such partially pinned domains will create their own magnetization in the direction that the material was pinned. This localized magnetization will cause different parts of the material to reside at different points of the hysteresis loop. The interaction between the pinned and

If a saturating magnetic field is applied to the material for an excessive duration, most of the magnetic domains will become pinned, and the material will remain in the state that it was pinned at. It should be noted that the selected MOFR is not a latching material, and the hysteresis data provided by the manufacturer [15] shows that the MOFR should have almost no degree of Faraday rotation when the magnetic field is absent (Fig. 4). However, it seems that these pinned domains behave as localized regions of magnetization within the material.

If a magnetic pulse is applied at a high speed (1 μs pulsewidth) for a short duration (1–10 s), it appears that only some of the material's domains will be pinned. This partially pinned material can become pinned at a smaller magnetic field than the unpinned material. The pinned domains can grow with further exposure to a pinning magnetic field.

Once the material becomes partially pinned, it can easily move between being pinned or being unpinned just with the interactions inside the material. This is because the pinned domains inside the material can interact with the unpinned domains, and move them into a state where they become pinned. In order to check that the pinned domains inside the material are creating a magnetic field that is affecting the material, one can measure the Faraday rotation of the material after it is pinned. If the material produces a different Faraday rotation when it is pinned, then the pinned region is affecting the magnetization of the material under test.

C. Pinned MOFR Material

In order to test our hypothesis for the pinned materials, the material must be pinned. Then, the level of Faraday rotation must be measured without an applied magnetic field. If the material produces Faraday rotation without the applied field, then the material has some sort of localized magnetization or the material is pinned. If pinning the material at different applied fields results in different levels of Faraday rotation, then the field that the material produces is not from the remanence.

In order to measure the Faraday rotation of the material in an optical system that does not have polarization maintaining properties, one must sweep through each of the initial polarization levels in order to achieve an accurate measurement. This polarization sweep was accomplished using a polarization controller at the input (Fig. 2). The setup was tested without the material, and then with two unpinned materials of type low moment Faraday rotator [15]. With two magnetooptic (MO) materials stacked back-to-back in this setup, 90° of Faraday rotation can be achieved. It should be noted that it is normal for the maximum power level to be offset from 0° when a polarization controller is included in the system. The addition of unpinned MO material into the system did not affect the maximum power level of the system which lay at 106°. The material was pinned by applying a large saturating magnetic field to the material until there was no longer an observable optical pulse from the oscilloscope. In order to determine that the pinning was the cause of Faraday rotation, measurements were taken without any MO material in place, with the unpinned MO material, and with the pinned MO material. The MO was pinned and unpinned several times to ensure that the results were accurate.

1) Unpinned Material Experiments: For the unpinned material measurements, there was very little rotation between the experiments with the most rotation between the unpinned materials at +12° of rotation.

This rotation can be explained if the material was not completely unpinned every time. This is likely because it is very difficult to ensure that all of the domains moved back into their original states.

2) Pinned Material Experiments: After sweeping the polarization of the pinned material, the maximum power level lay offset by −20 to −90° depending on the magnetic field used to pin the material (Fig. 5). As mentioned earlier, this range of values is likely because of the pinning of the material. The material seems to be pinned at different levels depending on the field applied. At smaller fields, not all of the domains in the material become pinned. It may seem possible that we are only capturing local changes due to domain wall movement. However, multiple tests at different levels of pinning fields show different levels of Faraday rotation.

IV. Conclusion

A pinned material acts as if the pinned domains are creating a particular magnetization inside the material. When the applied magnetic field is below a certain point, the material acts normally. However, if a large enough magnetic field is applied for a short period of time, the magnetic field begins to pin some domains into place. The interaction between these pinned domains, the unpinned domains, and the applied magnetic field can cause the material to change how it responds to an applied magnetic field. Another interesting observation is that once the applied field is released, the pinned domains on their own do not necessarily keep the material in the saturation region. The combined field of the pinned domains appears to be able to occupy multiple different locations along the magnetic hysteresis curve. It is interesting that the pinned material rotated only in the negative direction. It is possible if a negative saturating field is applied to the material to pin it, the pinning will occur in the opposite direction. Further research into domain wall movement in pinned materials is necessary to understand how pinned domains are produced.

By testing different states of pinning and unpinning the material, a characterization of pinning has been developed. It is observed that the application of a large magnetic field (225–500 G) causes the pinning in the material to occur. This means that several applications must consider the effect of pinning if large fields are produced for long periods of time. Pinning may prove to be useful. In the past, latching materials have been developed as potential low-energy devices for magnetooptic switching [8]. Pinning may be another way to achieve similar results if the process of pinning and unpinning can be more easily accomplished. A pinned material does have the advantage of being able to be pinned at different states.

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