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# Permittivity disorder induced Anderson localization in magnetophotonic crystals

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ABSTRACT

This theoretical study was carried out to investigate the permittivity disorder induced Anderson localization of light in one-dimensional magnetophotonic crystals. It was shown that the disorder create the resonant transmittance modes associated with enhanced Faraday rotations inside the photonic band gap. The average localization length of the right- and left-handed circular polarizations (RCP and LCP), the total transmittance together with the ensemble average of the RCP and LCP phases, and the Faraday rotation of the structure were also investigated. For this purpose, the off-diagonal elements of the permittivity tensor were varied for various wavelengths of incident light. The obtained results revealed the nonreciprocal property of circular eigen modes. This study can potentially open up a new aspect for utilizing the disorder magnetophotonic structures in nonreciprocal systems such as isolators and circulators.

## 1. Introduction

Anderson localization was first discovered by P. W. Anderson in 1958 in solid state physics [1]. This phenomenon is described upon the interferences of scattered electronic wave functions in disordered media. Currently the concept of the Anderson localization is extended to several areas of science including acoustic [2], microwaves [3], Bose-Einstein condensation [4] and optics [5–7]. Investigations on light localization in disordered structures have been the subject of intense attentions considering the wave nature of light and its electromagnetic description. For example, Bertolotti and co-workers have studied the localization characteristics of the binary multilayer structure versus the total length of the structure. They have reported the observation of non-localized modes or necklace states in disordered systems [8]. The main results of the researches on disordered one-dimensional structures can be summarized as “exponential decays of the transmittance with increasing the length of the disorder structure” [9].

In the past, the magneto-optical effects and Faraday rotation were utilized in practical and experimental physics [10]. The combining of photonic band gap properties of photonic crystals and magneto-optical effects through the inclusion of these materials into the periodic structures results in enhanced Faraday rotations [11]. The obtained structures, magnetophotonic crystals (MPCs), and their unique nonreciprocal characteristics, beside their miniaturized scales made them valuable candidates to be utilized in a wide area of nonreciprocal photonic applications such as isolators and circulators.

In this letter, it was shown that beside the periodic and defective MPC structures, the permittivity disordered magnetophotonic structures can be used to produce the resonance modes and enhanced Faraday rotations. To this aim, a calculation of the localization length and transmittance characteristics of the one-dimensional magnetophotonic structures as done. It was shown that when the permittivity of the magneto-optical layers is disordered, the resonant transmittance modes would be created due to Anderson localization and however, the separation of localization lengths of the circular polarizations (CPs) eigen modes tend to occur.

## 2. Model and method

A schematic of the considered one-dimensional magnetophotonic crystal structure is shown in Fig. 1. The structure consists of magneto-optical cerium substituted yttrium iron garnet (Ce:YIG) and dielectric $SiO_2$ layers, ordered in the *x*–*y* plane. The repetition number of the structure is 45 and the whole structure is surrounded by air, air/(Ce:YIG/$SiO_2$)$^{45}$/air. The thicknesses of the Ce:YIG and $SiO_2$ layers are 175 nm and 262 nm, respectively. Then the thickness of the unit cell of the structure is $d_{\text{unit cell}} = d_{\text{Ce:YIG}} + d_{SiO_2} = 437$ nm, and the structure has a total

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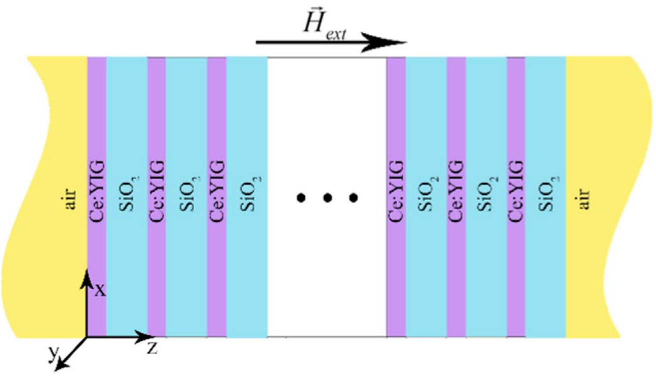

**Fig. 1.** The Geometry of the considered structure air/(Ce:YIG/SiO$_2$)$^{45}$/air with thicknesses of $d_{Ce:YIG} = 175$ nm and $d_{SiO_2} = 262$ nm.

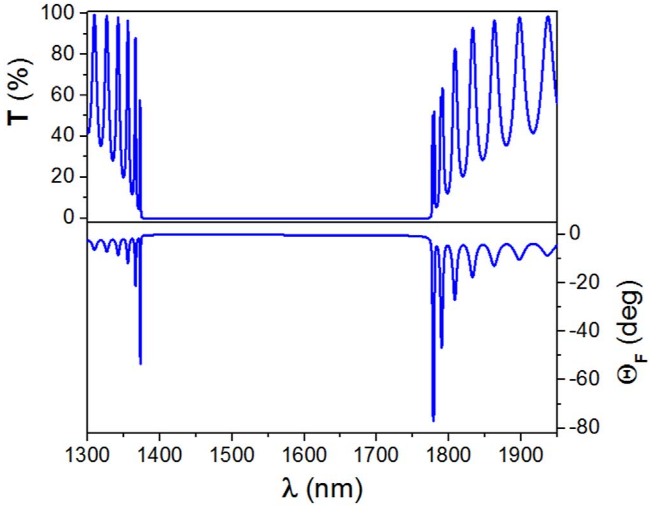

**Fig. 2.** The Transmittance and Faraday rotation spectra of the ordered ($\delta = 0$) structure air/(Ce:YIG/SiO$_2$)$^{45}$/air.

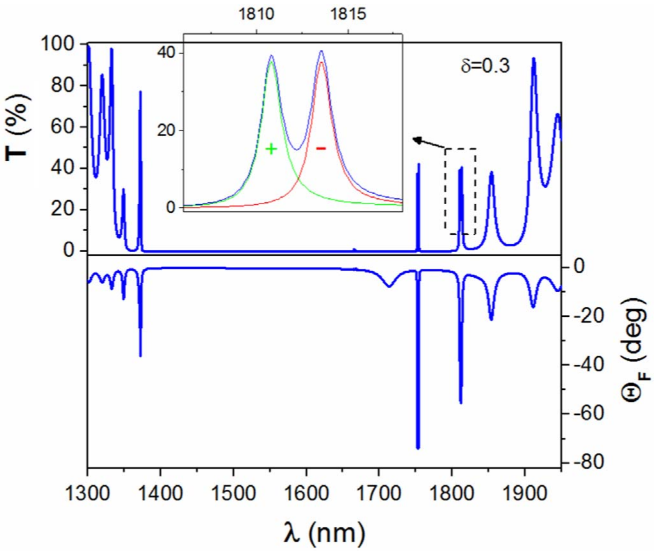

**Fig. 3.** The Transmittance and Faraday rotation spectra of the disordered structure air/(Ce:YIG/SiO$_2$)$^{45}$/air with $\delta = 0.3$.

length of $437 \times 45 = 19665\ \text{nm} \simeq 20\mu\text{m}$. The exterior magnetic field $\vec{H}_{ext}$ is applied on the structure in the $z$ direction.

The Ce:YIG layers are magnetized under the exterior magnetic field and in the considered geometry, their permittivity is described by a nondiagonal tensors:

$$\hat{\varepsilon}_{\text{Ce:YIG}} = \begin{pmatrix} \varepsilon_{xx} & iQ & 0 \\ -iQ & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}, \tag{1}$$

in which, $Q$ corresponds to the magnetic gyration. But the dielectric SiO$_2$ layers are unaffected by the exterior magnetic field and remain isotropic. Thus their permittivity is represented with a diagonal tensor with equal elements. The Ce:YIG layer permittivity tensor elements are $\varepsilon_{xx} = 4.884$ and $Q = 0.009$ under the saturable magnetic field and $\lambda = 1550$ nm for incident wavelength [12]. At this telecommunication wavelength, the SiO$_2$ layers have the permittivity tensor element of $\varepsilon_{SiO_2} = 2.19$ [13].

This study considered a normally incident linearly polarized light coming from air into the MPC structure and propagating in the $z$ direction. To calculate the transmittance characteristics of the structure, the 4 by 4 transfer matrix method was utilized. In this method, a transfer matrix was specified for each layer of the structure whose elements depend on the optical parameters and thickness of the layer. Then the total transfer matrix of the structure was obtained through multiplication of the transfer matrices of all layers. From the elements of the total transfer matrix, the right- and left-handed circular polarizations (RCP and LCP) transmission coefficients ($T_p$ and $T_m$, respectively), together with the total transmittance of the structure $\left(T = \frac{1}{2}\left(T_p + T_m\right)\right)$ were calculated. However, the RCP and LCP phases ($\varphi_p$ and $\varphi_m$, respectively) at the output plane of the structure along with the Faraday rotation of the output light were obtained $\left(\Theta_F = \frac{1}{2}\left(\varphi_p - \varphi_m\right)\right)$ [14].

In short wavelength approximation, the Anderson localization in the randomly disordered one-dimensional systems states that the localization length exponentially decays with the system length $L$ [15]. Then the dimensionless ensemble averaged localization length $\ell_{\text{loc}}$ can be expressed as:

$$\ell_{\text{loc}} = -\lim_{L\to\infty} \frac{N}{\langle \ln T \rangle}, \tag{2}$$

where $N$ represents the number of all layers of the structure and the angular brackets $\langle . .. \rangle$ denotes the ensemble averaging over the many randomly realized disordered structures. The multiplication of $\ell_{\text{loc}}$ by the unit cell thickness of the structure gives the real dimensional ensemble averaged localization length.

To obtain the permittivity disorder in the MPC structure, air/(Ce:YIG/SiO$_2$)$^{45}$/air, it was assumed that the diagonal element of permittivity tensor for each magneto-optical Ce: YIG layer fluctuates randomly around the normal value $\varepsilon_{xx}$ as $\varepsilon_{xx}(1 + \delta)$, where $\delta$ is a random number with uniform distribution in the range $\left[-\delta, +\delta\right]$. For the ensemble average of $10^6$ independently random realizations of the considered MPC structure are sampled.

## 3. Results and discussion

We calculated the transmittance and Faraday rotation spectra of the ordered MPC structure without including any disorder (Fig. 2). The photonic band gap (PBG) of the structure were realized in these spectra due to the destructive interferences of lights traveling through the layers of the structure. The sharp edges of the PBG were created around the 1375 nm and 1780 nm wavelengths. Meanwhile, the enhanced Faraday rotations were