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# Manipulating the light intensity by magnetophotonic metasurfaces

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ABSTRACT

We study numerically the possibility of controlling light properties by means of an external magnetic field. Considerable changes in the shape, value, and spectral position of the magneto-optical response are demonstrated in Voigt geometry for the transmitted light depending on the parameters of the magnetophotonic metasurface made up of nickel/silicon nanoparticles. The spectral overlapping of the fundamental magnetic and electric dipole Mie resonances leads to interference with a strong modification of phase relations, which manifests itself through an enhanced magneto-optical signal.



## 1. Introduction

A pursuit to use optical circuits as a faster alternative to electronic ones demands building blocks with the size smaller than the wavelength of light. These blocks are meant to work as active devices, which are capable of manipulating the light properties under the action of an external stimulus. The nature of such influence can be various: thermal [1], electrical [2,3], optical [4–6] or magnetic as well [7]. Modern photonics is going hand in hand with the magnetic science, thus opening new horizons for controlling the optical response via magnetic field [8] as well as magnetic domains of the sample via light impact [9]. The miniaturization of devices can be realized through nanostructuring of the materials. This gives rise to various types of resonances and optical effects that can be significantly enhanced under these conditions. Thus, being a multilayered system with alternative quarter-wavelength-thick magnetic and dielectric layers, magnetophotonic crystals can enhance Faraday effect by more than one order of magnitude [10–12]. This result accounts for the effect of slow light leading to an enlarged interaction time of light with a magnetic medium. A new apparatus for measuring Faraday rotation as low as 0.001° is suggested recently [13]. These nanostructures allow one to modulate polarization state of the light even at a femtosecond time scale [14]. An alternative way is to use plasmonic structures [8,15–18]. Excitation of the surface plasmon-polariton leads to the transverse magneto-optical Kerr effect being significantly increased [15]. The use of magnetoplasmonic crystals provides for the shape manipulating of a femtosecond pulse driven by an external magnetic field [17]. The excitation of local plasmons is another way to amplify the magneto-optical response [18,19]. A significant progress in studying magneto-optics is reached in systems with extraordinary transmission [20,21]. These resonances are highly dependent on the choice of geometry and environment, which makes it possible to shift the magneto-optical enhancement to the desired spectral region [22]. However, plasmonic materials have a certain disadvantage: a high imaginary part of the material refractive index results in undesirable losses at optical frequencies.

Optical resonances of high-index dielectric nanostructures are known for a high concentration of light energy at the nanoscale with low losses [23]. A strong magnetic dipole resonance, now called as *optical magnetism*, can be realized according to the exact Mie solution of light scattering by a small sphere, even if it is made of nonmagnetic materials [24]. Recently, this has been experimentally demonstrated for silicon nanoparticles in the visible spectral range [25]. The magnitude of the magnetic dipole resonance exceeds the electric dipole one. The increase of the particle size shifts these resonances to the infrared region, while multipoles of higher orders are moved to the visible part of the spectrum. Significant progress has been achieved in the development of not only silicon spheres' optical response, but also from other shapes of nanoparticles as well [26–29]. These nanoparticles are known for their high impact of the magnetic component of light leading to strong magnetic dipole resonances of the Mie-type. Furthermore,

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nanodisks made of materials with high refractive indices can enhance nonlinear optical response and oligomers of such nanoparticles also pave the way for new bright nonlinear phenomena [30,31].

Resonant nanoparticles can be arranged in the form of the so-called metasurfaces – subdiffractional arrays, which can shape the amplitude, phase, and polarization of the light wave on demand [32]. It has been revealed, that such structures can be used for a laser beam steering [33], an engineering light scattering patterns [34], for a creation of azimuthally and radially polarized light [35]. Interference of several modes in high-index dielectric or semiconductor nanoparticles can also be used to suppress resonant back-scattering and to enhance resonant forward-scattering of light [36].

The high-index dielectric nanostructures approach has recently been extended to magneto-optical materials [37,38]. It has been demonstrated that the magnetic dipoles excited in silicon nanodisks covered with a thin nickel film on top lead to the enhanced magneto-optical signal [38]. In this work, we numerically show the evolution of the magneto-optical response in hybrid Ni/Si nanoparticles arranged in the form of metasurfaces. The magneto-optical response of the metasurface can be controlled by tuning geometrical parameters of the structure, which leads to a significant increase of the effect as well as to the transformation of its shape and spectral position.

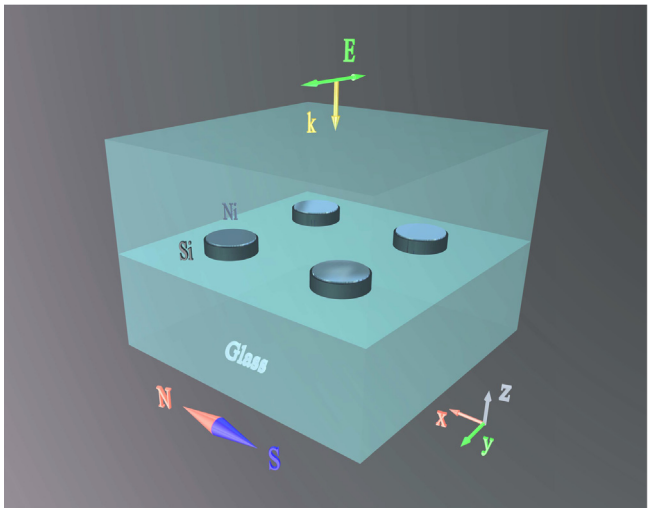


**Fig. 1.** Scheme of the model. 5-nm-thick nickel film covers 220-nm-thick silicon nanodisks. Subdiffractional array is organized by nanodisks with interparticle distance of 200 nm forming the magnetophotonic metasurface. The metasufrace is embedded in a dielectric environment with n = 1.5. An external magnetic filed is applied along the *X* direction, polarization of light is oriented along *Y* axis and the wavevector is collinear with *Z* axis.

## 2. Methods

Numerical calculations are performed on the basis of the finite difference time domain technique. This algorithm is implemented in commercial software FDTD Solutions, Lumerical Inc. [39], which is used in this work. Calculations are carried out for the 3D model. The boundary conditions for Z axis are perfectly matched layers, while they are periodic for X and Y. A plane wave under normal incidence (along *Z* direction) with a broadband spectrum is used in order to calculate zero-order transmittance spectra. The polarization direction is chosen along the *Y* axis. The external magnetic field is applied along the *X* direction. Thus, the transverse geometry of the magneto-optical effect, known as Voigt geometry for transmitted light, is examined. The magneto-optical response $\delta$ is defined as follows:

$$\delta = \frac{T(H) - T(0)}{T(0)}, \tag{1}$$

where $T(H)$ and $T(0)$ are transmittance in the case of an 'on' and 'off' state of the external magnetic field $H$, respectively.

As a sample under study silicon nanodisks with a thin nickel film on top are chosen (see Fig. 1). The silicon nanodisks have a height of 220 nm. A 5-nm-thick Ni layer is placed on top of the nanodisks. In order to rule out any inconsistency between the refractive indices under and above nanoparticles they are embedded into a dielectric material with the constant refractive index of 1.5. The spectral properties of the optical constants of Si [40] and Ni [41] are taken into account. The gyration of Ni is also supposed to be dependent on a wavelength [42]. The permittivity tensor of Si is isotropic while it is anisotropic for Ni. In the studying Voigt geometry, the non-diagonal permittivity tensor of nickel has the following form:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & ig \\ 0 & -ig & \varepsilon \end{pmatrix}. \tag{2}$$

Here, $\varepsilon$ is a dielectric permittivity and $g$ is a gyration vector. However, the software works only with diagonal matrices. According to this, permittivity tensor of the metal should be diagonalized. This can be realized by finding the eigenvalues and eigenvectors of the matrix. The unitary transformation that makes the permittivity tensor diagonal: $\varepsilon_{diag} = U\varepsilon U^{\dagger}$, where $U$ is a unitary matrix, $U^{\dagger} = U^{-1}$ is the complex conjugate transpose of $U$ and $\varepsilon_{diag}$ is diagonal matrix. The matrix $\varepsilon_{diag}$ is used by the software for calculations.

The field components should be also transformed with the eigenvectors. The user should define a matrix $U$ (by the means of a grid attribute object in the software, called matrix transformation) that converts the field components. In the case of magnetization in the *X* direction, the matrix $U$ has the following form:

$$U = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} & 0 & 0 \\ 0 & 1 & i \\ 0 & 1 & -i \end{pmatrix}. \tag{3}$$

Finally, a geometry object of disk should be connected with the created anisotropic nickel material through the parameter 'grid attribute name' in properties of the geometric object.

The varying diameter of the disk $d$ is simulated from 275 to 525 nm with a step size of 50 nm. The interparticle distance is fixed at 200 nm. Consequently, the lattice constant varies between 475 and 725 nm.

## 3. Numerical simulations

### 3.1. Optical spectroscopy

Transmittance spectrum of an all-dielectric metasurface formed by silicon nanodisks has been studied previously [34]. The first step for simulation in the framework of this study was to check whether magnetic and electric dipole modes are excited when the nanodisks are covered by a metal. Fig. 2(a) compares optical transmittance spectra of the all-dielectric structure without metal with the hybrid Ni/Si structure. The disks diameter is 275 nm. The right resonance around $\lambda = 944$ nm corresponds to the excitation of a magnetic dipole resonance, while the left dip ($\lambda = 870$ nm) is an electric dipole resonance. The distributions of the local electric and magnetic fields magnitude are shown in Fig. 2(b)–(i). The four upper panels represent the data in a horizontal cross-section. The

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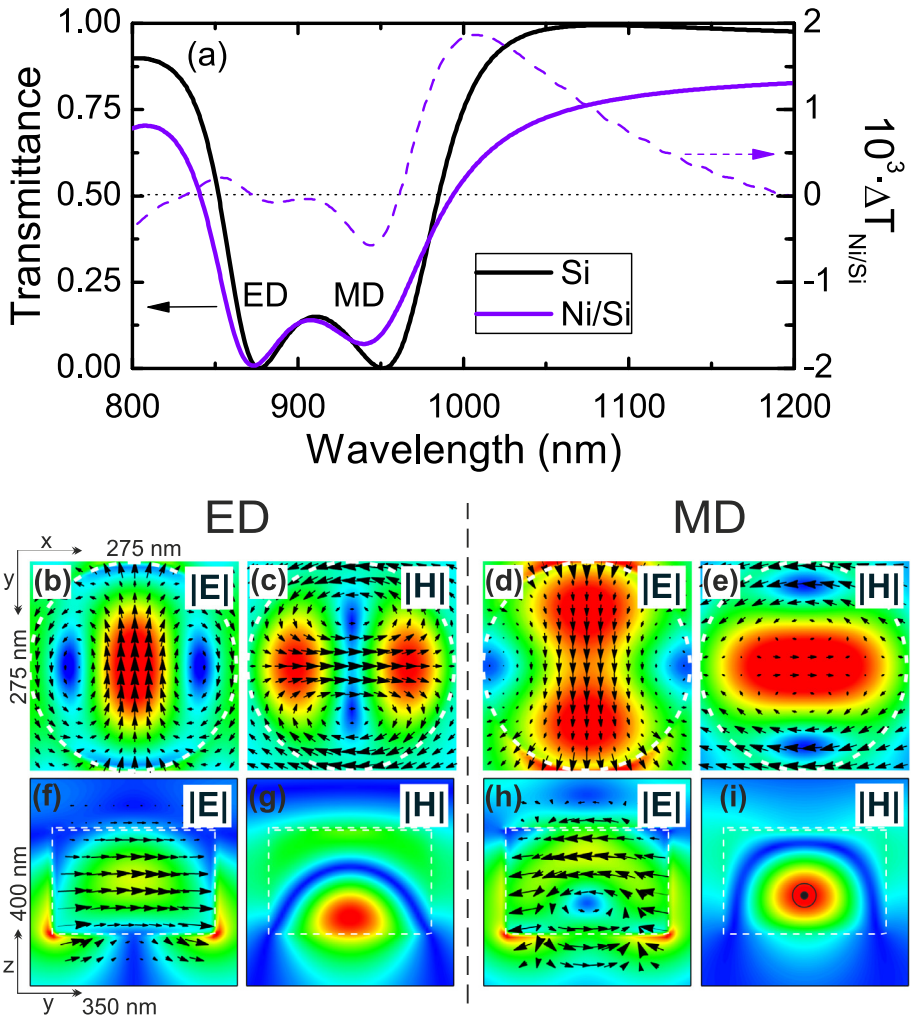


**Fig. 2.** (a) Optical transmittance spectra of the model with the diameter d = 275 nm for all-dielectric disks (black curve) and for Ni/Si structure (purple curve). A dash purple line is a differential signal of Ni/Si transmittance with and without external magnetic field $\Delta T_{Ni/Si} = T_{Ni/Si}(H) - T_{Ni/Si}(0)$. (b)–(i) Distributions of local electric and magnetic fields. The color maps represent the amplitudes of the local electric and magnetic fields, while arrows show their direction. (b)–(e) Local field distributions in *XY* plane for *z* equals to half of disk height. (f)–(i) Local field distributions in *YZ* plane through the center of the disk. (b), (c), (f), (g) Local field distributions for the electric dipole resonance ($\lambda = 870$ nm). (d), (e), (h), (i) Local field distributions for the magnetic dipole resonance ($\lambda = 944$ nm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

displacement currents form a loop generating a magnetic dipole (see panels (d), (e), (h), (i)). The panel (e) shows an antinode at the center of the disk for the distribution of the magnetic component of light, while the electric component (panel (d)) gives almost a node at this point. An opposite picture is observed for the electric dipole resonance: a node for the magnetic field distribution (panel (c)) and an antinode for the electric field (panel (b)). The color maps on the panels (f)–(i) represent a vertical cross-section in the plane of polarization, *ZY*. These figures confirm the electric nature of the excited Mie resonance for the wavelength of 870 nm on the panels (f), (g) and the magnetic nature of the resonance for the wavelength of 944 nm on the panels (h), (i).

When a nickel layer is introduced over of the silicon nanodisks three outcomes could be outlined (compare the black and purple solid curves in Fig. 2(a)): (I) the transmittance of the structure is reduced due to optical losses in the metal; (II) changing of the environment above silicon disks causes a mismatch between refractive indices on top and bottom interfaces and the modification of the optical contrast; (III) the height of the nanoparticles is slightly extended. The last two facts lead to a spectral shift of the resonances. A metal film over the dielectric disks turned out not to cancel the Mie resonances excitation.

The next step for simulation is to study the optical response when the diameter of Ni/Si disks varies, while height is fixed. Enlarging the disk diameter leads to a shift of the resonances to the red part of the spectrum (see Fig. 3(a)). However, the electric dipole resonance shifts more quickly comparing to the magnetic dipole mode, which leads to crossing of the two modes for a specific diameter of the disks.

The excitation of magnetic and electric dipole resonances reduces the transmittance of the sample down to 1%. However, low optical signal does not mean that magneto-optical response would be small [13,19–21,43]. For example, the similar values of transmittance were shown experimentally and numerically in magnetoplasmonic crystals in condition of surface plasmon resonance excitation [43]. The authors demonstrate the values of the intensity magneto-optical effect, namely transverse magneto-optical Kerr effect, up to 1% under transmission of 1%. Another example is a theoretical study of Faraday rotation, which is polarization effect, in a low-transmittance regime, in condition of the localized plasmon resonance excitation of gold nanoprticles embedded in a magnetic dielectric layer [19]. These studies allow for expectation the existence and an enhancement of the magneto-optical response in the studying magnetophotonic metasurfaces.

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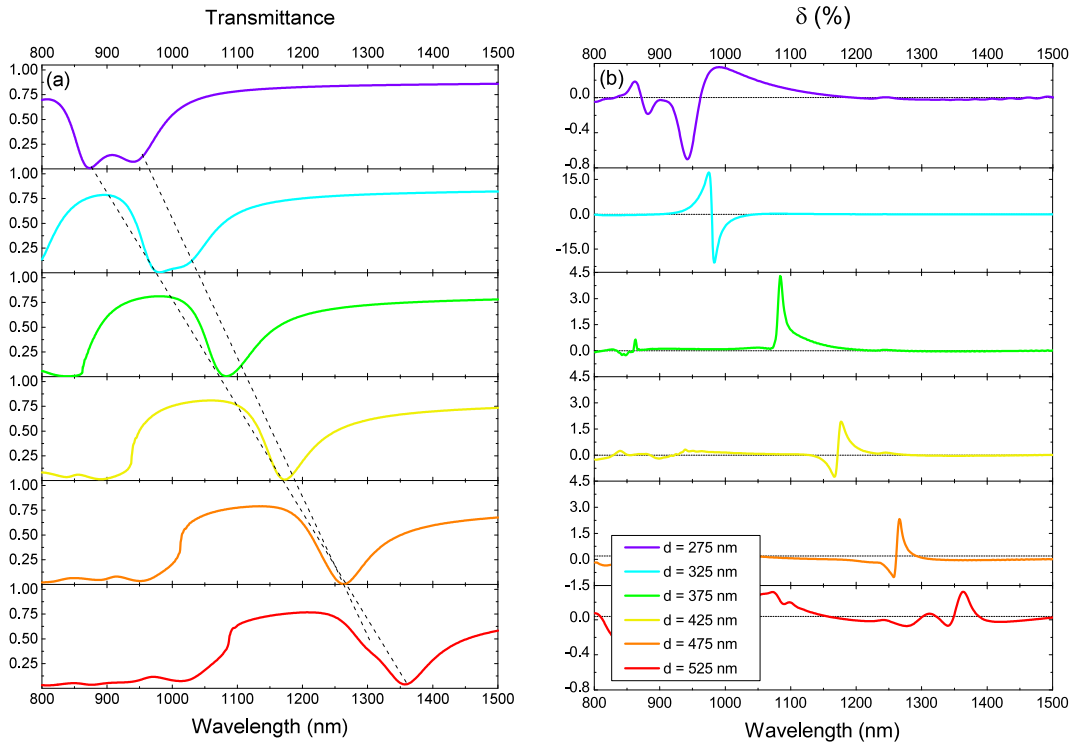


**Fig. 3.** Optical transmittance (a) and magneto-optical (b) spectra for the model depending on the diameter of nanodisks. Purple curve: d = 275 nm, cyan curve: d = 325 nm, green curve: d = 375 nm, yellow curve: d = 425 nm, orange curve: d = 475 nm, red curve: d = 525 nm. Dash black lines on panel (a) are guides to eye showing the shift of the resonances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 3.2. Magneto-optical spectroscopy

The magneto-optical response of magnetophotonic metasurfaces can be now simulated. In the studied Voigt geometry switching-on of the external magnetic field results in a spectral shift (The Faraday rotation, which is polarization effect, is also studied. The results are presented in the section Appendix A). A large value of the $\delta$ corresponds to the large spectral shift. The $\delta$ is dependent on $T(0)$ in the denominator (see Eq. (1)). It means that if $T(0)$ drops to zero, the magneto-optical response increases significantly. Based on that we first calculate the differential transmittance signal of the magnetophotonic metasurface in case of both in the presence $T(H)$ and in the absence $T(0)$ of external magnetic field $\Delta T_{Ni/Si} = T_{Ni/Si}(H) - T_{Ni/Si}(0)$. The dash line in Fig. 2(a) proves that an applying of the magnetic field shifts the transmittance spectrum. Fig. 3(b) shows the spectral dependence of the magneto-optical response $\delta$. The smallest diameter of $d = 275$ nm demonstrates two resonance features (see purple curve). As was mentioned above, the right peculiarity correlates with the excitation of magnetic dipole resonance and the left one with the electric dipole mode. The magnitude of the effect is greater for the magnetic dipole and reaches the value of $\delta = -0.7\%$. When the diameter increases by 50 nm (the cyan curve) a robust enhancement is observed. Constructive interference of two modes brings a large value of the effect $\delta = \pm 20\%$ and the Fano line shape of the resonance with equal contributions of positive and negative values of the effect. The magneto-optical effects are strongly depends on the phase of the resonance. When two resonances are spectrally overlapped, the resulting phase can lead to significantly increase of the magneto-optical effects. This value is almost 30 times larger comparing this diameter with the previous one.

The following increase in diameter (the green curve) shifts the phase responses relative to each other; interference is not so pronounced. The magneto-optical signal is reduced in comparison with the previous case and becomes equal to $\delta = 4\%$. This value is larger contrary to non-overlapping modes (the purple curve). Another interesting result is the absence of negative values of the magneto-optical signal. The spectral overlap of the two resonances introduces Fano line shape that depends on the phase relation. In this situation the phase sum suppresses the negative values of the effect. The next two steps of increasing the diameter (the yellow and orange curves) lead to the appearance of negative values of $\delta$ ($\delta = -1.2\%$) and the decreasing of a maximal value of the effect down to approximately $+2\%$. This asymmetry is described by the phase relation of the two resonances. Finally, when the electric dipole resonance is again far away from the resonance of the magnetic dipole mode, there is no interaction of phases and the magneto-optical response decreases down to the value of the separate resonances equals to $\approx \pm 0.3\%$.

## 4. Discussion

An important feature is that the maximal value of magneto-optical effects is observed not for the absolute spectral coincidence of magnetic and electric dipole resonances, but for the case, when their phase relations have a significant difference. The metasurfaces are considered as a planar analogues of metamaterials, where the main problem is to generate a magnetic dipole to manipulate light scattering. The ability of metasurfaces for controlling the phase, amplitude, and polarization of the incoming light plays a vital role in development of optical devices. The growing potential belongs to the phase engineering at the material interfaces that open new possibilities for light control. In plasmonics, $2\pi$ phase control can be realized independently by tunable resonances, each of them has a $\pi$ phase shift over the resonance [33,36,44,45]. The sensitivity of the magneto-optical response to the phase of the resonance has recently been shown in nickel nanodisks as a variation of a magneto-optical hysteresis loop depending on the probing

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light wavelength with respect to the position of a local plasmon resonance [7]. Here, we combine the manipulation of the phase by all-dielectric metasurfaces with the magneto-optical phase sensitivity.

The effect of the resonant enhancement of the magneto-optical signal in condition of Mie modes excitation is quite expected. The external magnetic field modifies material constants of the nickel layer changing the resonance conditions. The result of this changes is the redistribution of the electromagnetic fields leading to the modification of an optical signal (transmittance, reflectance and absorption). The experimental demonstration and numerical verification of the enhancement of the magneto-optical response for the individual magnetic dipole, separated from the electric dipole mode, has recently been shown in an array of far-standing Ni/Si nanodisks [38]. A really intriguing question is the behavior of the magneto-optical signal in the case, when the electric and the magnetic dipole resonances are in the spectral vicinity. While wavelengths of these modes separated, the change of the magneto-optical response is the effect of modification of resonant properties due to modification of the environment. If the resonances are close enough one should take into account effect of interference of fields, scattered by these dipoles. The key parameter now is a complex amplitude, i.e. not only the magnitude, but the phase of the scattered waves as well. The dipole modes respond in a different way for the action of the external magnetic field. Consequently, the mentioned magnitudes and phases vary differently. It leads to the change in the far-field interference between these two modes. The solution, revealing the global extremum, i.e. maximal constructive interference, leads to the drastically amplified magneto-optical response.

In this study we demonstrate that applying the external magnetic field to a specially designed hybrid Ni/Si structure one is capable of manipulating light significantly.

## 5. Conclusions

In conclusion, magnetophotonic metasurfaces are proposed to control light properties by an external magnetic field. The magnetophotonic metasurfaces under study are composed of high-index silicon nanodisks covered with a 5-nm-thick nickel film. Considerable changes in the shape, value, and spectral position of the magneto-optical response are demonstrated in Voigt geometry for the transmitted light. Controlling the magneto-optical response is realized through the excitation of magnetic and electric dipole Mie resonances; a significant enhancement of the effect up to $\delta = 20\%$ is attributed to the interference of these modes. The high value of the magneto-optical signal is reached for low transmittance. Recently, an enhancement of the intensity magneto-optical effect up to 1% was experimentally and theoretically demonstrated in small transmittance regime [43]. Taking into account this achievement, it looks reliable to measure the spectral properties of the magneto-optical response of the magnetophotonic metasurfaces. This experiment can be realized in combination of null-ellipsometry technique based on high-frequency phase modulation [46,47] and apparatus proposed in Ref. [48], where transverse magneto-optical Kerr effect up to 6% is experimentally observed. The use of magnetophptonic metasurfaces can be suitable for photonic devices dynamically controlled by an external magnetic field.

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## Appendix A. Numerical calculation of Faraday rotation spectra

The permittivity tensor of Ni (2) and the transformation matrix $U$ (3) should be corrected for the case, when Voigt geometry is replaced with Faraday geometry, because the direction of the magnetic field is changed from $X$ axis to $Z$ axis. Now permittivity tensor has the following form:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon & ig & 0 \\ -ig & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix},$$

while transformation matrix $U$:

$$U = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i & 0 \\ 1 & -i & 0 \\ 0 & 0 & \sqrt{2} \end{pmatrix}.$$

Fig. 4 presents the Faraday rotation spectra depending on the nanodisks diameters. The enhancement of the signal is caused by the excitation of the magnetic and the electric dipole modes. The spectral shift of the resonant features follows the shift of the dipole

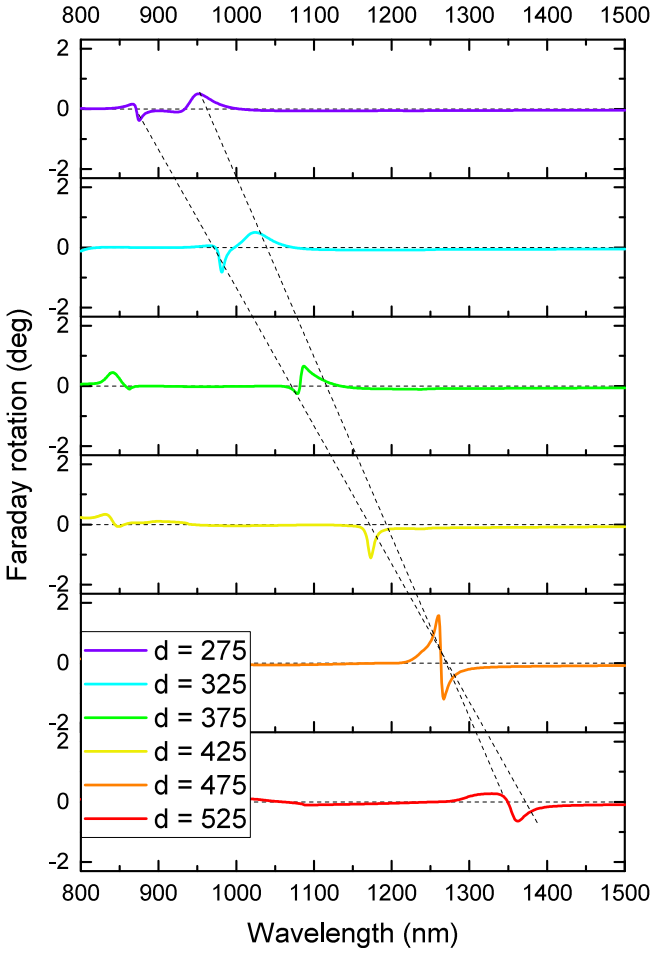


**Fig. 4.** Faraday rotation spectra for the model depending on the diameter of nanodisks. Purple curve: d = 275 nm, cyan curve: d = 325 nm, green curve: d = 375 nm, yellow curve: d = 425 nm, orange curve: d = 475 nm, red curve: d = 525 nm. Dash black lines are guides to eye showing the shift of the resonances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resonances due to the increase of the disks' diameter (see Fig. 3(a)). It is interesting to note, that the maximal enhancement of the polarization effect (up to 2°) is observed for the other parameters of the model ($d = 475$ nm) comparing to the intensity effect ($d = 325$ nm). It is known, that Faraday effect is maximal for constructively interfering waves [11]. The maximal Faraday rotation for this configuration of the sample can be explained by the increasing of front-scattering and the suppression of back-scattering waves from nanoparticles. The experimental and numerical verification of the increasing of the front-scattering waves for this parameters has been shown previously [34]. Thus, the maximum rotation of the polarization plane is observed for the nanodisks diameter of $d = 475$ nm.

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