Enhanced magneto-optical effect in three layer based magnetoplasmonic structures

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Abstract

In this article we introduce a magnetoplasmonics (MP) planar nanostructure with enhanced transverse magneto-optical (MO) activity. For this goal MO characteristics of magneto-structures containing both metal layer and linear array of (metal) nanorods are analyzed. We explore three types of structures with nanorods and compare their features based on transvers magneto-optical Kerr effect (TMOKE) with the corresponding one for conventional three layers MO structure. Comparison between the values of TMOKE signals in two structures (proposed and conventional) shows more than one order of magnitude improvement. Accordingly, the refractive index sensitivity of the offered structures, specially with one and three types of Au nanorod arrays, appearance more than 2 order of magnitude larger than the conventional Au/Co/Au three layer MO structures. This notable response enhancement becomes serious affair in MP biosensing applications. We believe that our idea in these proposed nanostructures can be used in any other three layer based MO structures in the literature. On this basis, we apply this scenario to other types of such MO structures which leads to improvement in their MO activities and whereupon in their refractive index sensitivities.

Keywords Surface plasmons (SP) · Magneto-optical effects · Optical sensors · Nanorods

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1 Introduction

Surface plasmon resonance (SPR) is an interesting effect which is utilized in advanced optical sensing (Verma et al. 2015; Homola 2008, 2006). This sensing mechanism have some positive features such as real-time detection, without fluorescent labeling identified chemical biological species with high resolution (Larrroulet 2015). Nowadays, SPR sensors used in some important applications like double-stranded DNA recognition (Slinchenko et al. 2004), pathogens sensing (Oh et al. 2003), and DNA sequences manifestation (Wang et al. 2004). Propagated and localized surface plasmons occurred on flat plane and curved (nanoparticle) metal/dielectric interfaces, respectively, are two branches of SPR phenomenon (Maier 2007; Klimov 2014). Collective motions of free electrons of metal at metal/dielectric interface which are excited by an TM electromagnetic wave, and coupled with it, produce a confined surface plasmon wave (SPW) propagating along the interface (Maier 2007). Different phase matching methods are exist for launching SPW’s in several SPR device configurations such as prism coupling or attenuated-total-reflection (ATR), which is used in our analysis of this article, near field excitation by fiber tip (Maier 2007) and gratting coupler (Singh and Hillier 2008).

In artificial materials (metamaterials) which are construct from meta-atoms, suitable combination of metal and dielectric materials with subwavelength dimensions, surface plasmon resonances and excitations have the central role in their performances. A multi-band metamaterial absorber in the terahertz regime (up to 2 THz) using two identical split rings having opposite opening directions which are connected by a rectangular patch was reported (Wang et al. 2022a) is a typically work in this category of SPR applications. Before this research another terahertz metamaterial absorber in higher frequency region (1.8–3.6 THz) with dual-/triple-band feature was designed and investigated (Wang et al. 2019).

Many SPR new sensors are in the terahertz region with the model of metamaterial structure. For instance, terahertz metamaterial absorber using two square metallic patches over a continuous metallic ground, with a separation larger, in its unit cell obtained two response peaks with near 100% absorbance. The narrow line-width absorption peak is used for sensing application in this research (Wang et al. 2020). In other reported study terahertz metamaterial with perforated square-patch unit sell is used as a multi-band terahertz superabsorber for sensing of refractive index change of the embedded material in the rectangular hole (Wang et al. 2021). In the similar research category, sensing performance of the quad-band terahertz metamaterial absorber used three metallic strips in its basic cell, in order to form an asymmetric I-type resonator, was investigated (Wang et al. 2022b).

Magneto-optical properties of a ferromagnetic metal film, like Co and Fe, is improved when it lays adjacent to a noble metal film, due to SPR excitation on the noble metal and enhancement of electromagnetic field at its interface with ferromagnetic metal. On the other hand, due to the large absorption less of ferromagnetic metals the electromagnetic field of those excited SPW is rather weak and has a low sensitivity to the refractive index of surrounding medium. Therefore, the combination of two types of metals also compensate this sensing deficiency. Simple and the first magnetoplasmic sensor like Co/Au demonstrate more sensitivity compared to standard SPR sensor (Sepúlveda et al. 2006). The first experimental and theoretical study of MO properties of noble metal-ferromagnetic-metal for Au/Co/Au model with enhancement of the magneto-optical response, for three magnetization directions, is reported in Hermann et al. (2001).
In the presence of a magnetic field, the dielectric tensor of the ferromagnetic material becomes non-diagonal (Zvezdin and Kotov 1997). The effect of an external magnetic field on the polarization state of the light transmitted and reflected by a magnetic material depends on the relative orientation of the magnetic field and the plane of incidence. When the magnetic field or the magnetization is set perpendicular to the incident plane and parallel to the sample plane, known as the transverse magneto-optics kerr effect (TMOKE), there is no change in polarization state and only the magnitude of the reflected light is affected by the magnetic field. In magnetoplasmonic (MP) structures, the enhancement of MO activity is occurred due to surface plasmon resonances (Hermann et al. 2001; Safarov et al. 1994; Ferreiro-Vila et al. 2008). In array of multilayer nanodisc, composed of Au/Co/Au, were separated from continuous Au/Co/Au trilayers by a dielectric spacer shows how localized surface plasmon (LSP) excitation leads to improvement of the MO activity of the whole structure (Armelles et al. 2009).

It has been shown that the response of these sensors can enhance by using of MO properties of layered structures containing magnetic materials (Sepúlveda et al. 2006; González-Díaz 2007; Manera et al. 2014). Several magneto-optical surface plasmon resonance (MOSPR) sensors have already been shown to have better properties than traditional SPRs ones (Regatos et al. 2011; Clavero et al. 2010; Kämpf et al. 2012; Rizal et al. 2018a, b, 2019). Improvement of gas sensing in magneto-optical SPR sensor by using and adding a nano-porous TiO₂ layer on the Au/Co/Au multilayer is reported (Manera et al. 2011). In the last decade, the TMOKE technique has been attracted the attention of researchers because of its potential in sensors (Regatos 2010; Manera et al. 2011, 2012; Pellegrini et al. 2014; Caballero et al. 2016; Grunin et al. 2016; Ignatyeva et al. 2016; Li et al. 2018; Rizal and Belotelov 2019). By measuring the TMOKE signal in Au–Co–Au films perforated with a periodic array of subwavelength holes, can leads to a large enhancement of the figure of merit of this type of hybrid MP crystal sensor (Caballero et al. 2016).

Here, we introduce a new three layer magnetoplasmonic nanostructure, with nanorod array by adjusting the individual thicknesses of each layer, and proved it possess more than one 100-fold sensitivity increase over a standard MP sensor. Furthermore, we also expected this design leads to sensitivity enhancement in other three layer based MP heterostructures have been introduced in the literature until now. In the Au/Co/Au trilayer structures, it has been shown that multi-layer magnetic structures with more than one magnetic layer increase the sensitivity of the sensor (Kämpf et al. 2012). Among different kinds of sensors plasmonic ones are more efficient than the others, owing to the high sensitivity of surface plasmon resonance (SPR) to changes of surrounding medium (Afsheen et al. 2021).

In this article, we introduce and analyze an idea for modification of conventional three layer based magnetoplasmonic structures in order to enhance magneto-optical features of these configurations. For this goal, we design a structure composed of an array of Au nanorods lays on the Co layer and both are over a thin Au layer. Light is coupled to this structure from the Au layer side by using the usual Kretschmann method. One of the important results obtained from our simulation analysis belongs to the sharp variation of the transverse MO effect (TMOKE signal), around the plasmon resonance angle, wherein we have a minimum reflectance from the structure. The amplitude of this sharp rising and lowering in $\Delta R/R$ diagram is large compared to corresponding values for other three layer MP structures, at least one order of magnitude is improved. Also, the refractive index sensitivity of our proposed structure is improved comparing to the ordinary Au/Co/Au trilayers MP structure. This comparison is also pronounced specially
for other three layer based MO structures such as Cr/Au/Fe/Au and Cr/Co/Cr/Au and an eligible improvement is resulted.

2 MO parameter and considered structures

In our study, we use the TMOKE signal in which the sample magnetization is located on the sample plane and is perpendicular to the plane of incidence. In this category, the permittivity of the magnetic layer includes off-diagonal components related to the Voigt vector $Q$ as follow (Ross et al. 2016):

$$\vec{\varepsilon} = \begin{pmatrix} 1 & 0 & iQ_y \\ 0 & 1 & 0 \\ -iQ_y & 0 & 1 \end{pmatrix}$$  \hspace{1cm} (1)

$Q_y$ represents the MO constant of the material. The amplitude of the Voigt vector is taken to be considered as $Q_y = 0.055 - i0.013$ for Co (Osgood et al. 1997). We use for the diagonal components ($\varepsilon$) of the Co permittivity tensor from the dielectric function data introduced Johnson and Christy. In our study, the MO feature of the proposed structure is according to the calculation of reflectivity, $R$, versus incident angle for a light with a wavelength of 653 nm. Therefore the transverse Kerr signal $\Delta R/R$ versus incident angle is computed from its conventional definition as (Ross et al. 2016):

$$\frac{\Delta R}{R} = \frac{R_{pp} (+H) - R_{pp} (-H)}{R_{pp} (+H) + R_{pp} (-H)}$$  \hspace{1cm} (2)

where $R_{pp} (+H)$ and $R_{pp} (-H)$ are the reflectance values for opposite magnetization directions. A schematic diagram of our structure under the Kretschmann excitation method is presented in Fig. 1a.

![Fig. 1](image)

**Fig. 1**  a Schematic diagram for our proposed, used in simulation medium, structure consists of Au layer (16 nm), magnetic material Co(4.5 nm), an array of Au layer nanorods (Au NRs), or in a brief symbol Au(16 nm)/Co(4.5 nm)/Au NRs. The radius of each rod and the separation between them are 13 nm and 34 nm, respectively. This structure is launched by prism coupling (BK7) from above. b Picture of a conventional magnetoplasmonic three layer structure Au(16 nm)/Co(4.5 nm)/Au (2 x 13) nm, the thickness of each layer is the same as panel (a)
To investigate the magneto-optical properties theoretically, we consider an Au layer with 16 nm thickness over a 4.5 nm thin layer of cobalt which are in turn stay on a one-dimensional array of Au nanorods. The radius of each rod is equal to 13 nm and the separation between them is 34 nm (center to center). All this structure is coated over a cylindrical BK7 prism, see Fig. 1a. The light is coupled to this nanostructure from the prism side and the magnetic field is applied along the y-direction. The second panel in Fig. 1 shows the schematic representation of the conventional trilayer MO structure with the same geometry of the proposed structure, panel (a). The simulation results obtain for this standard MO structure is used as a criteria for the present study. The other two appropriate structures which are also considered in this article with two and three types of nanorods, see panels (a) and (b) in Fig. 2, respectively.

Here, in this study we using the numerical simulation COMSOL software (version 5.6) employing the finite-element frequency domain algorithm. Also, periodic boundary conditions is applied in the perpendicular to the incident direction of light. Rexciting the structure and monitoring the reflected light from the above of the structure. Also we use the mesh size in the simulation as 27 nm.

For experimental realization of the proposed structure, a layer of Au with thickness of 16 nm and then a layer of cobalt with thickness of 4.5 nm can be deposited on a BK7 prism using DC sputtering method. Next, a layer of Au is coated on the Co layer with thickness of 26 nm. Then, highly ordered gold nanorods with a radius of 13 nm and a separation distance of 34 nm can be created through the deposited 26nm Au layer using electrolithography method. The challenges in the design and optimization of the proposed structure is belong to the fabrication of regular nanorods in the form of an array collection.

3 Result and discussion

According to Fig. 1a we calculate by simulation the reflectivity from the proposed structure as a function of incident angle for a specific laser wavelength of 653 nm. The results of this study for two directions of magnetization or magnetic field (H) are plotted in Fig. 3a.
The same investigation is also carried out for the ordinary trilayer structure, Fig. 1b, and the results are demonstrated in Fig. 3b. As it is shown from Fig. 3 the difference between reflectivity values for each direction of the H is very small, see for example the inset in panel (a). The reflectivity behavior of our MO structure, 3(a), has the main difference comparing to the corresponding one for the ordinary MO structure, 3(b). The increasing of the angular spread of around the reflection minimum by an order of magnitude is this clear distinction. Furthermore, owing to this broadening the minimum value of reflectivity occurred at a larger light incident angle, see Fig. 3a.

On the other hand, from a plasmonic point of view, occurring the minimum with wide angular distribution represents the excitation of surface plasmon (SP) with higher confinement and larger dissipation in our structure. This feature is confirmed by comparing the electric field (its magnitude) spatial distribution across the two structures at the angle of minimum reflectivity, see two panels in Fig. 4.

As it is shown from panel (b) of this figure more energy of the SPP mode is mostly inside the homogenous surrounding dielectric environment (here is air) in ordinary MO structure. Contrary to this behavior is shown in a structure containing the rods and its penetration to the surrounding medium (air) is very low and the fields are also trapped by the nanorods, see Fig. 4a. Therefore, due to this important feature that appeared in our offered structure, we expect the improvement of coupling between surface plasmon resonances.
with magnetic layer (Co) and accordingly enhancement of its MO characteristic. We are now in a position that to introduce the analysis of the transverse magneto-optical Kerr signal (TMOKE), Eq. (2), for structures depicted in Fig. 1. The variations of ∆R/R for incident angles for structures in panels (a) and (b) of this figure are indicated by the same panel names in Fig. 5. The TMOKE signal response of our structure, panel (a), has a sharp variation around the minimum reflectivity angle. The same behavior is also shown for ordinary trilayer structure around its minimum reflectivity angle, see Fig. 5b. The most specification of the former is a large increase in its maximum and minimum values of this MO signal when compared to the corresponding values in the latter. Nearly, this structure experienced more than one order of magnitude improvement in its TMOKE response.

Here we also examine the MO properties of the other two structures introduced in Fig. 2 by the same procedure discussed above. In the second structure, Fig. 2a, two kinds of nanorods are utilized despite the first proposed structure, Fig. 1a, in which only one type of nanorod is utilized. Smaller nanorods, with the half radius of adjacent rods, are between larger nanorods with the same lattice constant, 34 nm. Figure 2b demonstrates the third proposed MO structure with three types of metal nanorods such that between larger nanorods two models of smaller ones are situated, with radii of 3 nm and 1.5 nm,
respectively. The light reflectivities from these MO structures for opposite directions of magnetic fields are computed and the results are illustrated in Fig. 6. According to Fig. 6b, the shape of the reflectance diagram for third structure has a symmetry around its minimum, like the corresponding curve for the first proposed structure, see Fig. 3a. There is no such symmetry for the reflectance curve in the second proposed structure, see Fig. 6a. On the other hand, the width of the valley around the minimum reflectance in this figure is smaller than the corresponding one for the third structure, see Fig. 6b. The physical reason for this difference can be understood when the electric field distribution across the two structures at the angle of minimum reflectance are compared to each other, look at the two panels in Fig. 7.

Following the different colors around the nanorods in these figures one to be able to find that the field confinement to the metal nanorods is slightly increased in three types nanorods structure, panel (b), concerning other structure, panel (a).

In the other words, due to the shape of reflectance around its minimum in Fig. 6b more confined surface plasmon modes are launched in the structure of Fig. 2b concerning corresponding modes in the structure of Fig. 2a. After this physical inspection of the reflectivity properties of the two proposed structures introduced in Fig. 2 here we investigate their MO features. Inside the TMOKE signal of these conformations we observe
the sharp high values of maximum and minimum adjacent to the corresponding angle of minimum reflectance, see two parts of Fig. 8. The same characteristic we also show before in the TMOKE signal for the first proposed structure with a single type nanorod, see Fig. 5a.

The main difference between TMOKE signals of these structures compared to the corresponding signal of the first proposed configuration (Fig. 4) is that in the latter the value of maximum (minimum) is nearly two times the same quantity values in the former.

The final study which is in accord with our motivation in the present task is about the sensing properties of the proposed structures. For this goal considering the refractive index of the surrounding medium of the nanorods experienced a little change concerning the vacuum index ($n = 1$). According to Fig. 9, one can show that our proposed structure with single-type nanorods has exceeded refractive index sensitivity compared to trilayer structure, assimilate, respectively, panel (a) with panel (b). The separation between TMOKE signal curves for successive little variation of refractive index, $\Delta n = 0.002$, is more pronounced in the proposed MO structure. Furthermore, the magnitude of the maximum (minimum) in

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**Fig. 9**  a TMOKE signal as a function of the incident angle at the wavelength of 653 nm for the different refractive indexes of the surrounding medium. a for the proposed structure with one type of nanorods, b for conventional trilayer MO structure, see the respectively structures in Fig. 1a, b

**Fig. 10**  a TMOKE signal as a function of the incident angle at the wavelength of 653 nm for the different refractive indexes of the surrounding medium. a for the proposed structure with two types of nanorods, b for the offered structure with three types of nanorods, see Fig. 2a, b, respectively
each TMOKE curve is also increased by augmenting the refractive index by a little value in each step, see Fig. 9a. This feature is not remarked in ordinary MO structure, see Fig. 9b.

The same investigation we also carried out for other proposed MO structures with two types of nanorods, regarding panel (a) of Fig. 10, and three kinds of nanorods, considering panel (b) of this figure. The general behavior of TMOKE curves for these structures, Fig. 10, is the same as the corresponding one for the first proposed structure, look Fig. 9a, but with a moderate enhancement characteristic. Here, we use the standard criterion for evaluating the sensitivity enhancement of these proposed MO structures.

Theoretical analysis of the response of a magnetoplasmonic TMOKE sensor with respect to variation of the refractive index or its index sensitivity can be defined as (Pellegri and Mattei 2014):

\[ \eta = \frac{\theta_{\text{max}}}{\Delta S} = \frac{\partial S}{\partial \theta} \times \frac{\partial \theta_{\text{max}}}{\Delta n_{\text{en}}} \] (3)

Here, S represents the maximum value of the TMOKE signal that occurred at a certain angle (\(\theta_{\text{max}}\)) for each \(n_{\text{en}}\), where \(n_{\text{en}}\) is the refractive index of the medium around the nanorods. Then from Eq. (3) one can find that the two factors contribute to expected sensitivity (\(\eta\)), the slope of the TMOKE curve as a function of the incident angle (\(\theta\)) and the angular displacement of such curve when \(n_{\text{en}}\) changes. We extract the slope of two lines pertaining to these factors from all TMOKE curves appearing in Figs. 9 and 10 for obtaining the sensitivity of each contemplated MO structure. For example, the linear variation of the maximum TMOKE signal versus its occurrence angle (\(\theta_{\text{max}}\)), extracted from Fig. 9a, is represented in Fig. 11a. Panel (b) of this figure also produce from Fig. 9a and shows that the line belongs to alteration of \(\theta_{\text{max}}\) when the refractive index changed step by step.

Hence, from Fig. 11 the sensitivity of the proposed MO structure with a single type of nanorods is obtained equal to 33.313. After applying the same scenario for other two concerned MO structures, we computed the sensitivity values of 2.491 and 11.847 for structures two and three types of nanorods, respectively. Therefore, based on these results proposed MO structures with one, two, and three types of nanorods increased the refractive index sensitivity by the factors of 468.5, 35, and 166.6, respectively, when compared to the same parameter for conventional trilayer MO structure, produced from Fig. 12 and is equal to 0.0711. This comparison is classified in Table 1. According to this table, among these

![Fig. 11](https://example.com/f11.png) a Linear relation between maximum TMOKE signal versus its occurrence angle, whenever the surrounding refractive index of the MO structure with single kind of nanorods is changed. b the change of angle, in which the TMOKE signal becomes maximum, versus the variation of the refractive index.
structures, the sensitivity enhancement of the first one (first proposed structure) is more pronounced, and it to be helpful in many exhaustive sensing applications.

In order to confirm our idea, as discussed above for Au/Co/Au three layer structure, have a positive effect on MO activity of other three layer based MO structures we examine this scenario for two other three layers famous MO structures. As it is shown from Fig. 13a, b we present an electric field distribution and TMOKE characteristic of the modified type of one of those. The conventional geometry of this configuration which is reported in reference (Regatos 2010) is in the form of Cr/Au/Fe/Au. Here, based on the our proposal only the last Au(30 nm) layer is replaced by a designed single array of Au nanorods, see this structure in Fig. 13a. The improvement of the TMOKE signal is emerged after this modification and it is understand by comparing the panels (b) and (c) of Fig. 13. By calculating the refractive index sensitivity deduced from these figures, in accord to above discussion Eq. (3), after one can obtain the values of 48.28 and 2.73 for modified and original structures depicted in panels (b) and (c), respectively. In this case the enhancement factor, the ratio of two values, is equal to 17.7. The same procedure we act on the another conventional MO structure in the literature (Sepúlveda et al. 2006) in order to check the improvement model worked very well. The obtained results for this task is demonstrated in different panels of Fig. 14. Panel (a) shows the modified structure of the original one, which is Cr/Co/Cr/Au layers, and part (b) is the TMOKE signal of this structure for different refractive index of the surrounding medium of the nanorods. The small variation of the refractive index (around n = 1.3363) produces an effective change in the TMOKE diagrams of the modified structure, see Fig. 14b. However, this behavior is not shown in the TMOKE signal of the original three layer structure, Cr/Co/Cr/Au layers, see panel (c) of Fig. 14. It is interesting to calculate the sensitivity, according to Eq. (3) and its discussion, by using of these two TMOKE diagrams. The results obtain from these computations manifest an

![Fig. 12](image)

**Table 1** The refractive index sensitivity enhancement of the three proposed MO structures, compared to the same quantity for conventional trilayer Au/Co/ Au structure (with the value of 0.0711)

| MO structure                              | Sensitivity values | Enhancement factor |
|-------------------------------------------|--------------------|--------------------|
| Au/Co/ single type of Au nanorod          | 33.313             | 468.5              |
| Au/Co/ two types of Au nanorods           | 2.491              | 35                 |
| Au/Co/three types of Au nanorods          | 11.847             | 166.6              |
improvement factor of 224.6 in the refractive index sensitivity of this modified structure, see Table 2. It is a remarkable enhancement, more than two order of magnitude, in sensitivity of the structures with MO activity.

In our study also examined the effect of other noble metal materials instead of Au nanorods such as Ag on the MO response of these modified structures. For this investigation we use the structures which are introduced respectively in Figs. 1a, 13a and 14a with one except in each one so that the single type Au nanorods are exactly replaced by Ag nanorods. Furthermore, Mo response of these modified structures are compared to the corresponding response for the original ones, when concerning Ag nanolayer instead of Ag nanorods in each structure. To pursue this procedure for the structures presented respectively in Figs. 1a, 13a and 14a we obtain and summarize the corresponding results in Figs. 15, 16 and 17, respectively. In accord to these figures one can show the field distribution around the structure and the TMOKE response of the configuration with Ag nanorods or Ag nano-layer, follow up panels (a) and (b) and (c) in each figure, respectively.

The refractive index sensitivities of these structures are computed and classified in Table 3. The third column of this table reports the (sensitivity) enhancement factor of the modified structure, with Ag nanorods, compared to original one, with Ag nanolayer. Based on this column information Ag nanorods mostly affect the sensitivity of Cr/Au/Fe/Ag (nanorods) structure, in spite of the weakly affect of Au nanorods on the
corresponding feature of this structure. Compare the enhancement factors in Table 3 with the information in the first row of Table 1 and all data in Table 2 which demonstrate the effect of single type Au nanorods on MO sensitivity of these structures.

Therefore, both Au and Ag nanorods in these modified structures, these noble metal nanorods replaced by the corresponding metal nano-layer in the original structures, improved their index sensitivity feature. But in this enhancement policy the role of Au nanorods is more prominent.

![Fig. 14](image)

**Table 2** The refractive index sensitivity enhancement for other modified structures (Au nanorods instead of last Au layer), see Fig. 13a, b. The second column of this table is compared with the corresponding sensitivity value of each original structure, here we computed the values of 2.73 for Cr/Au/Fe/Au and 0.364 for Cr/Co/Cr/Au and then the third column data are generated

| MO structure                      | Sensitivity values | Enhancement factor |
|-----------------------------------|--------------------|--------------------|
| Cr/Au/Fe/Au nanorods (Fig. 13a)   | 48.28              | 17.68              |
| Cr/Co/Cr/Au nanorods (Fig. 14a)   | 81.7535            | 224.6              |
In Table 4 we compare the index sensitivity, according to Eq. (3), of different three layer based MO structures with the corresponding quantity when these reported structures modified by our proposal, last Au layer is replaced by single type Au nanorods. The first three rows of this table are also mentioned in Tables 1 and 2. The data in the last three rows are new and alike the data in other rows the structures belong to those are explicitly investigated but their structures are not demonstrated in detail inside the article. From Manera et al. (2011) we only restated the TMOKE signal based index sensitivity for Cr(2 nm)/Au(25 nm)/Co(6 nm)/Au(15 nm), see the corresponding data in row 4.

In the last two rows of Table 4 the sensitivity of the original structures, for different sizes of layers and for two wavelengths, introduced in Pellegrini and Mattei (2014) are calculated according to our simulation method and using of the corresponding TMOKE curve for each structure. As mentioned before the same procedure we also used for original MO structures reported in first three rows of Table 4. Finally, one can show that after applying our scenario, as explained in parenthesis in every row of column 3, to every MO structure presented in the first column of Table 4 the index sensitivity is increased and consequently the MO activity is enhanced, see last column.

It is evident that the fabrication of one dimensional array of metal nanorods on a flat layer (like Co) is intrinsically challenging task by usual techniques such as e-beam
lithography and photolithography. However, in order to overcome high cost processing and long time of construction fast and low price fabrication methods such as pattern transferring by direct mechanical deformation of a soft resist using a hard mold or stamp is suggested. Therefore, volume production of our proposed nanostructure, metal nanorods instead of metal layer, with low build up time and expense is possible by the recently developed process of nanoimprint lithography (NIL) technique.

4 Conclusion

Here, we show that the magnetoplasmonic performance of nanostructures that contain both noble metal thin layer and nanorod array, with a suitable diameter and lattice constant, is better than the corresponding one for conventional MP structure with two metal layers around the thin magnetic material. This comparison is based on simulation of their TMOKE signals as a function of light incident angle. The maximum (minimum) value of the TMOKE signal evince more than one order of magnitude growth in the proposed structure with one type of nanorods. Also, improvement of more than two order of magnitude in refractive index sensitivity of the offered structures, (Au/Co/Au nanorods) with one and
three types of nanorods, recommend these magnetoplasmonic design structures for more competent biosensing applications in the progressive magneto-optic field. Finally, it is predicted that by using of this idea in other three layer based magnetoplasmonic structures with an adjusting design (for nanorods) leads to improvement of their magneto-optic features. We apply and exam this scenario for other seven cases of layered MO structures reported in literature, summarized in Table 4, in order to proved this claim. This task leads to confirm the prediction and one of the structures (Cr/Co/Cr/Au nanorods) shows...
Table 4 Comparison between refractive index sensitivity, defined by relation (3), of different MO structures reported in literature and the sensitivity of the corresponding structure when modified according to our scenario (single type of Au nanorod instead of last Au layer)

| MO structure reported in literature | Refractive index sensitivity by TMOKE curve | Index sensitivity after applying our schema | Enhancement factor |
|------------------------------------|---------------------------------------------|-------------------------------------------|-------------------|
| Au (16 nm)/Co(4.5 nm)/Au(26 nm)    | 0.0711 (Au nanorods (13 nm) instead of last Au layer) | 33.313 (Au nanorods (13 nm) instead of last Au layer) | 468.5 |
| (Ref. (González-Díaz 2007) for $\lambda = 653$ nm) |                                           |                                           |                   |
| Cr(2 nm)/Au(5 nm)/Fe(5 nm)/Au(30 nm) (Ref. (Regatos 2010) for $\lambda = 632$ nm)) | 2.73                                           | 48.28 (Au nanorods (9 nm) instead of last Au layer) | 17.68 |
| Cr(2 nm)/Co(7.5 nm)/Cr(3 nm)/Au(18 nm) (Ref. (Sepúlveda et al. 2006) for $\lambda = 632$ nm)) | 0.364                                      | 81.7535 (Au nanorods (9 nm) instead of last Au layer) | 224.6 |
| Cr (2 nm)/Au (25 nm)/Co (6 nm)/Au (15 nm) (Ref. (Manera et al. 2011) for $\lambda = 632$ nm) | 0.0331                                      | 0.5771 (Au nanorods (8 nm) instead of last Au layer) | 17.435 |
| Cr (2 nm)/Au (39.6 nm)/Co (2 nm)/Au (17.8 nm) | 0.7                                         | 2.107 (Au nanorods (8 nm) instead of last Au layer) | 3.01 |
| Cr (2 nm)/Au(25.3 nm)/Co(4.3 nm)/Au (28 nm) (Ref. (Pellegrini and Mattei 2014) for $\lambda = 633$ nm) | 0.62                                         | 4.605 (Au nanorods (8 nm) instead of last Au layer) | 7.43 |
| Cr (2 nm)/Au(38.1 nm)/Co (2 nm)/Au (17.1 nm) | 4.47                                         | 9.101 (Au nanorods (13 nm) instead of last Au layer) | 2.036 |
| Cr (2 nm)/Au(27.2 nm)/Co(3.9 nm)/Au (28.8 nm) (Ref. (Pellegrini and Mattei 2014) for $\lambda = 850$ nm) | 3.81                                         | 28.96 (Au nanorods (13 nm) instead of last Au layer) | 7.601 |
a remarkable enhancement (with respect to original one), more than two order of magnitude, in its refractive index sensitivity feature. However, in practice the custom fabrication techniques of nanostructures which are contain an array of metal nanorods accompanied by some challenges compared to the fabrication task for metal nanolayers. In spite of this fact, it is possible to overcome this obstacle by using of some rapid and inexpensive developing fabrication techniques such as nanoimprint Lithography.

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**Data availability**  The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

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