Role of avoided crossing and weak value amplification on enhanced Faraday effect in magnetoplasmonic systems

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Enhancement of magneto-optical effects in hybrid magneto-plasmonic systems has attracted considerable recent attention because of their potential for building non-reciprocal nanophotonic devices. Quantitative understanding of the fundamental origin and contributing mechanisms for the enhancement is crucial for optimizing applications. Here, we unravel different physical origins of the giant enhancement of Faraday rotation and ellipticity in a hybrid magneto-plasmonic system, namely, waveguided magneto-plasmonic crystal for excitation with transverse electric (TE) and transverse magnetic (TM) polarized light. With TE polarization excitation, where the surface plasmons are not directly excited, the natural weak value amplification of Faraday effects appearing due to the spectral domain interference of Fano resonance is the dominant cause of the enhancement. For TM polarization excitation, on the other hand, waveguide-plasmon strong coupling and its universal manifestation of avoided crossing plays an important role, leading to maximum enhancement of the magneto-optical effects in the avoided crossing regime.

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Hybridization of magneto-optic (MO) materials with plasmonic nanostructures enables magnetic-tuneable multifunctional nano-devices that is capable of providing precise control over its plasmonic and magnetic properties^{1,2}. Moreover, such systems are also known to exhibit giant MO effects (Faraday, Kerr effect etc.)^{2–8}. Note that the nonreciprocal nature of the MO effects is crucial for developing optical isolators³, modulators, and optical-magnetic data storage devices^{1,8} etc. Usually, the weak MO effects of the available materials are a major stumbling block towards their applications in nano scale devices. Significant efforts have therefore been delivered in the last few years to demonstrate enhancement of both the magneto-optical Kerr effect and the Faraday effect in magneto-plasmonic nanostructures^{2,4,7}. Earlier approaches for increasing the MO activity of the systems were mostly based on the excitation of surface plasmons, where the near field enhancement associated with the surface plasmons leads to substantial enhancement of MO responses of samples^{9,10}. In this regard, a recent study that has demonstrated giant enhancement of Faraday rotation in a waveguided magneto-plasmonic crystal (WMPC)³ system, has attracted a lot of attention. Subsequently, some other related studies have reported even larger enhancement of Faraday rotation in various magneto-plasmonic systems using similar approach^{4,6,11}. In most of these studies, the enhancement of MO effects is attributed to either the surface plasmon-induced near field enhancement or to the coupling of the waveguide-plasmon-polariton^{2,4,6}. For both the cases, the enhanced MO effect is related to the excitation of the surface plasmon resonance, which in case of the investigated planar structures can only be excited using transverse magnetic (TM) polarization of light. In contrast to this understanding, our recent investigation demonstrated a large enhancement of both the Faraday rotation and ellipticity in a Fano resonant WMPC system for incident TE polarized light where no surface plasmons were directly excited¹². This observation indicated possibility of another important mechanism of the enhancement, namely, the natural weak value amplification (WVA) of Faraday rotation and ellipticity due to spectral domain interference of Fano resonance. Proper understanding of the different mechanisms of enhancement of the MO effects in hybrid magneto-plasmonic system and their dependence on the various physically accessible parameters of the system and of excitation light is of paramount importance for both fundamental and applied interests.

The concept of weak measurement and WVA was introduced by Aharonov, Albert, and Vaidman^{13–17}. This special measurement process involves three steps, quantum state preparation (preselection), a weak interaction, and post-selection on a final quantum state that is nearly orthogonal to the initial state. The outcome of such measurement, the so-called weak value, may not only become exceedingly large and lie outside the eigenvalue spectrum of the observable but can also assume complex values^{13–15}. The quantum mechanical concept of WVA can be understood within the realm of wave optics and thus most of the experiments on weak measurements are performed in classical optical setting^{17–23}. The WVA concept can be interpreted as near destructive interference between the eigenstates of the measuring observable as a consequence of mutually near orthogonal pre and post selections of the system states^{13,14}. Based on this simple interferometric philosophy of WVA, we had initially shown that a similar situation arises in the spectral domain interference of Fano resonance that leads to natural WVA of small Faraday rotation and ellipticity in WMPC¹², which acts as the weak interaction in this scenario. An analytical model for natural WVA in Fano resonance demonstrating the amplification of small polarization anisotropic effects around the

Fano destructive point was given in our previous publication. However, in the context of the WMPC, such a model¹² was derived for a restricted case where the resonance frequencies for the TM and TE quasiguided modes are the same. Yet, it is important to investigate a more general scenario of natural WVA of Faraday effects in Fano interference, which is expected to provide a better understanding about the role of WVA in the enhancement of the MO properties in magneto-plasmonic crystals. Here, we have therefore addressed this issue by adopting differences in the resonance frequencies for the TE and the TM waveguide modes. This enabled us studying the dependence of the WVA of Faraday effects in Fano resonance (with TE polarization excitation) on the resonance frequencies of the TM and the TE modes and their varying extent of spectral overlap that can be tuned by changing the geometrical parameter of the plasmonic crystal system. In contrast to the TE polarization excitation, for the TM polarization excitation, the underlying physical mechanisms for the enhancement of the MO effects are expected to be rather complex and are more interesting due to simultaneous involvement and coupling of the waveguide mode and the plasmon mode in such hybrid system. As there appears to have different possible mechanisms of the enhancement of MO effects in magneto-plasmonic crystals^{2–4,10} including the one of natural WVA¹², the question arises whether there is a common physical origin of the enhancement irrespective of the input polarization state or are there different mechanisms that contribute with varying strengths depending upon the excitation polarization and the geometrical parameters of the WMPC. The main purpose of this work is to address this important question and to shed light upon the competing roles of the different contributing mechanisms, namely, the natural WVA and the purity of Fano resonance¹², near field enhancement effects due to the excitation of the surface plasmons², resonance enhanced cross coupling between the TE and TM polarization^{3,4}, the waveguide-plasmon strong coupling^{3,4}, and the related phenomenon of avoided crossing and so forth on the giant enhancement of magneto-optical effects (Faraday rotation and ellipticity). The results of our study establish that while for TE polarization excitation, the natural WVA of Faraday effects due to Fano resonance is the dominant cause of the enhancement, for TM polarization excitation, the waveguide-plasmon strong coupling plays the leading role in the enhancement of the MO effects. This study also provides quantitative understanding on the observed giant enhancement of magneto-optical effects and provides potentially useful information on optimizing plasmonic crystal structure for its potential applications in nanoscale devices.

Results

Theoretical framework of natural WVA of Faraday effects in a Fano resonant WMPC. We have recently developed a theoretical treatment for natural WVA of polarization rotation and ellipticity in the spectral domain interference of Fano resonance¹². Briefly, in this model, the spectral (ω) variation of the polarized electric field of Fano resonance^{24,25} is modeled as the interference of a y -polarized frequency-independent continuum mode with an optically active narrow resonance mode that exhibits a small rotation (α) and ellipticity (χ). However, in the context of demonstrating WVA of the Faraday effects in WMPC system, this model¹² was restricted to the case where both the TM and the TE waveguide modes have the same resonance frequency. Here, we extend this model to a more generalized case of Fano interference in the WMPC by including different resonance fre-

quencies for the TE and the TM waveguide modes. The resultant polarized field can be expressed as

$$E_s(\omega) \approx \left[\frac{q-i}{\varepsilon(\omega)^{\text{TE}} + i} (\cos \alpha \cos \chi - i \sin \alpha \sin \chi) \hat{x} + \frac{q-i}{\varepsilon(\omega)^{\text{TM}} + i} (\sin \alpha \cos \chi + i \cos \alpha \sin \chi) \hat{y} \right] \quad (1)$$

Here, $\varepsilon(\omega)^{\text{TE}} = \frac{\omega - \omega_0^{\text{TE}}}{(\gamma/2)}$, $\varepsilon(\omega)^{\text{TM}} = \frac{\omega - \omega_0^{\text{TM}}}{(\gamma/2)}$, where ω_0^{TE} and ω_0^{TM} are the resonance frequencies of the TE and the TM waveguide modes respectively and γ is the width of the resonance, which is assumed to be of similar magnitude. The q parameter is related to the coupling of the modes and determines the characteristic asymmetry of Fano spectral line shape. WVA of small polarization rotation (α) and ellipticity (χ) takes place as a consequence of near destructive spectral domain interference between the two modes with slightly different polarization states (which arises due to the presence of a small optical activity of the narrow resonance mode that acts as the weak interaction parameter in this weak measurement scenario) around the frequency of the Fano spectral dip $\omega_F = (\omega_0^{\text{TE}} - \frac{\gamma}{2})$ corresponding to $\varepsilon^{\text{TE}} = -q$. Note that ω_F is the frequency corresponding to exact destructive interference, where the phase difference between the TE quasiguided mode and the broad continuum becomes $\Psi(\omega_F) = \pi$ and the ratio of the amplitudes between them is unity. At close vicinity of ω_F , near destructive spectral domain interference takes place between the two modes with simultaneous small amplitude offset ($\varepsilon_a(\omega)$) and phase offset ($\varepsilon_p(\omega)$). It is this near destructive spectral interference between the two modes that mimics the near orthogonal pre and post-selections of states (small overlap of states $\varepsilon_{a/p}$) in conventional optical WVA. It is pertinent to note that for the ideal case of natural WVA in Fano resonance (which occurs for $\omega_0^{\text{TE}} = \omega_0^{\text{TM}} = \omega_0$), there are common amplitude and phase offset ($\varepsilon_{a/p}$) parameters for both the TE and the TM waveguide modes, which can be obtained in terms of the parameters of Fano resonance as

$$\varepsilon_a(\omega) \approx \frac{\left(1 - \sqrt{\frac{\varepsilon^2 + 1}{q^2 + 1}}\right)}{\left(1 + \sqrt{\frac{\varepsilon^2 + 1}{q^2 + 1}}\right)}; \varepsilon_p(\omega) = \pi - \Psi(\omega) = \pi - \tan^{-1} \left[\frac{q + \varepsilon}{1 - q\varepsilon} \right] \quad (2)$$

However, in the general case, the amplitude and phase offset parameters for TE ($\varepsilon_{a/p}$) and TM ($\varepsilon'_{a/p}$) interfering modes will differ owing to their different resonance frequencies, which can be expressed as

$$\varepsilon_a(\omega) \approx \frac{\left(1 - \sqrt{\frac{\varepsilon^2 + 1}{q^2 + 1}}\right)}{\left(1 + \sqrt{\frac{\varepsilon^2 + 1}{q^2 + 1}}\right)}; \varepsilon_p(\omega) = \pi - \Psi(\omega)^{\text{TE}}; \varepsilon(\omega) = \frac{\omega - \omega_0^{\text{TE}}}{(\gamma/2)}$$

and

$$\varepsilon'_a(\omega) \approx \frac{\left(1 - \sqrt{\frac{\varepsilon'^2 + 1}{q'^2 + 1}}\right)}{\left(1 + \sqrt{\frac{\varepsilon'^2 + 1}{q'^2 + 1}}\right)}; \varepsilon'_p(\omega) = \pi - \Psi(\omega)^{\text{TM}}; \varepsilon(\omega) = \frac{\omega - \omega_0^{\text{TM}}}{(\gamma/2)} \quad (3)$$

Using a similar framework of WVA¹², it can be shown that as in case of the ideal WVA, the real and the imaginary WVA of the polarization rotation α and ellipticity χ are manifested as $\varepsilon_{a/p}$

dependent large changes in the polarization state of light (described by Stokes vector elements), which acts as the pointer here (see Supplementary Note 1). However, here there are two sets of the small amplitude and the phase offset parameters ($\varepsilon_{a/p}$ for TE and $\varepsilon'_{a/p}$ for TM) incorporated in the WVA equation (see Eq. S6 of Supplementary information). One important difference from the ideal WVA case is that, as the TE and TM waveguide modes spectrally moves away from each other, one cannot simultaneously obtain a very small value of both set of the amplitude and the phase offset parameters $\varepsilon_{a/p}$ and $\varepsilon'_{a/p}$ at any given frequency around the Fano spectral dip ω_F , which is desirable for optimal WVA. Consequently, the maximum achievable amplification of polarization rotation α and ellipticity χ gets limited in this scenario. In contrast, for the ideal WVA scenario ($\omega_0^{\text{TE}} = \omega_0^{\text{TM}} = \omega_0$), this condition is easily obtained around ω_F leading to the maximum achievable amplification. We emphasize that the WVA does not break down even if one is observing the amplification at relatively larger amplitude and phase offsets, only the maximum magnitude of WVA decreases with slight deviation from the ideal behavior, which is more accurate for small offsets (see also results of the model presented in Supplementary Fig. 1).

Enhancement of MO effects in WMPCs for TE polarization excitation as a manifestation of interferometric natural WVA in Fano resonance.

The WMPC system comprises of a periodic array of noble metal nanostructures on top of a dielectric waveguiding layer, which is made of MO materials that exhibit Faraday rotation and ellipticity. The coupling of the spectrally broad surface plasmon mode in the metallic nanostructures or the photon continuum (depending upon the excitation polarization of light) with the narrow quasiguided photonic modes in the waveguiding layer leads to Fano resonance. We used finite element method (FEM)²⁶ for simulating the polarization resolved transmittance spectra from such system (see Methods). A schematic illustration of the FEM simulation of transmission and MO spectral responses of the WMPC is presented in Fig. 1. The WMPC system investigated in this study consists of gold (Au) grating on top of a thin yttrium-bismuth iron garnet (Y-BIG) film and the substrate is taken to be quartz. The MO active Y-BIG film serves as the waveguiding layer and also exhibits Faraday effect in the presence of an external magnetic field (see Methods). The simulated transmittance spectra ($E = \hbar\omega = 0.83$ to 2.067 eV) and Faraday rotation and ellipticity for varying geometrical parameters of the WMPC with TE polarization excitation are summarized in Fig. 2. The transmission spectra (Fig. 2a, e, i), the spectral variation of the observed Faraday rotation ψ (Fig. 2b, f, j) and the observed net ellipticity ξ (Fig. 2c, g, k) of the WMPC are shown for varying periodicity d (Fig. 2a, b, c), width w (Fig. 2e, f, g) and height h (Fig. 2i, j, k) of the Au grating. Several observations can be made. Prominent signatures of Fano resonance with asymmetric spectral line shape are observed in all the transmission spectra with TE polarization excitation (Fig. 2a, e, i). Here, the surface plasmons are not directly excited and hence the Fano resonance^{27–29} arises due to the interference between the spectrally narrow quasiguided resonance mode with an ideal photon continuum. Importantly, giant enhancement of Faraday rotation (Fig. 2b, f, j) and ellipticity (Fig. 2c, g, k) are observed around the Fano spectral dip ($E = \hbar\omega_F$) for all the geometrical parameters of the WMPC. In agreement with previous reports³⁰, the Fano spectral dip is observed to gradually move towards shorter frequency (or energy $E = \hbar\omega$) with increasing periodicity (d) of the grating (Fig. 2a). The magnitudes of the enhanced Faraday rotation ψ (Fig. 2b) and ellipticity ξ (Fig. 2c) exhibit an interesting trend with varying d —these increase to a maximum value for a

Fig. 1 The waveguide magneto-plasmonic crystal (WMPC). **a** A schematic illustration of the finite element method (FEM) simulation of Faraday rotation ψ in the transmission spectra of the WMPC system. The direction of the transverse magnetic TM (x) and transverse electric TE (y) polarized light electric fields are perpendicular and parallel (respectively) to the axis of the Au gratings in the WMPC. **b** The WMPC system comprises of gold (Au) gratings on top of a thin yttrium-bismuth iron garnet (Y-BIG) film and the substrate is taken to be quartz. The Y-BIG film serves as the waveguiding layer and additionally exhibit Faraday effect in the presence of an external magnetic field. The thickness of the Y-BIG film (t) and the periodicity (d), width (w), and height (h) of the Au gratings are marked.

certain value of periodicity and then follow a gradual decrease. The maximum magnitudes of the enhanced Faraday rotation ($\psi \sim 1.551^\circ$) and ellipticity ($\xi \sim 1.559^\circ$) of the WMPC are obtained for a value of $d = 550$ nm (Fig. 2b), as compared to the corresponding average bare film rotation and ellipticity of 0.28° and 0.1° , respectively. Neither the value of the width w nor the height h of the Au grating has any significant influence on the quasi-guided modes and hence the resulting Fano spectral line shape of the WMPC is not sensitive to variations of the w and the h -parameters of the grating (Fig. 2e, i). Accordingly, the magnitude and spectral variation of both the Faraday rotation (Fig. 2j) and ellipticity (Fig. 2k) do not exhibit appreciable variation with the change in the height h of the grating. Similarly, with varying width w of the grating, the Faraday rotation ψ (Fig. 2f) and ellipticity ξ (Fig. 2g) exhibit only weak variations (Faraday effects seem to be marginally stronger for $w = 120$ nm as compared to others). The spectral variation of the transmitted TM polarization intensities with TE polarization excitation are also plotted for each of the varying geometrical parameters of the WMPC (Fig. 2d, h, l). In general, the TM polarized intensities are considerably weak and approach their respective minima near the Fano spectral dip where maximum magnitudes of Faraday rotation and ellipticity are observed. This rule out the possibility of the role of the resonance enhanced cross-coupling of the TE and the TM quasiguided modes in the enhancement of the Faraday effect. The observed enhancement of the Faraday rotation and ellipticity around the Fano spectral dip corresponding to near destructive spectral domain interference between the quasiguided mode and the photon continuum is thus indicative of the prominent role of the natural WVA of Fano resonance for TE polarization excitation. This aspect is therefore investigated in further details by studying the dependence of the Faraday effect enhancement on the periodicity of the grating and through its natural weak value interpretation. As we proceed further, we note that we have also provided the near field distribution of both the TE and the TM polarizations around the Fano spectral dip (Supplementary Fig. 3), which confirms the dominance of the TE polarized field and the waveguiding nature of both the TE and the TM polarized fields around the Fano dip (see Supplementary Note 3 for details).

Figure 3 summarizes the results of natural WVA interpretation of Faraday rotation and ellipticity enhancements for TE polarized excitation for the Fano resonant WMPCs with two different values of periodicity of the Au grating ($d = 550$ nm, Fig. 3(a–f) and $d = 650$ nm, Fig. 3(g–l)) and having the same width and

height $w = 120$ nm and $h = 100$ nm, respectively. The spectral ($E = 0.83$ to 2.067 eV) variations of both the Faraday rotation ψ (Fig. 3a, g) and ellipticity ξ (Fig. 3b, h) are plotted along with the transmitted intensity profiles of the WMPCs. In order to analyze these results using the natural WVA formalism of Fano resonance, the spectral line shape of the transmitted intensity is first fitted with Fano intensity formulae (Eq. S3 of Supplementary information). The relevant Fano resonance parameters, namely, the central frequency of the interfering narrow resonance of the quasiguided mode ω_0^{TE} , width of the narrow resonance γ , the Fano spectral asymmetry parameter q are estimated from this fitting. These are subsequently used to determine the exact values of the frequency corresponding to the Fano dip $\omega_F = (\omega_0^{\text{TE}} - \frac{q\gamma}{2})$ and the amplitude offset (ϵ_a) and the phase offset (ϵ_p) parameters (using Eq. 2) in the natural WVA formalism. When the resonance frequencies of the TM and the TE quasiguided modes perfectly overlaps ($\omega_0^{\text{TE}} = \omega_0^{\text{TM}} = \omega_0$) there are common amplitude (ϵ_a) and phase offset (ϵ_p) parameters (as per Eq. 2 and Eq. 3). As discussed previously at the frequency corresponding to the spectral domain destructive interference (ω_F), both the offset parameters (ϵ_a, ϵ_p) are zero and as one moves spectrally slightly away from ω_F , both the ϵ_a, ϵ_p weak measurement parameters vary simultaneously (shown in Fig. 3d). The complex WVA (simultaneous real and imaginary WVA) of the weak Faraday effect is accordingly manifested as large enhancement of both the Faraday rotation and ellipticity when ($\epsilon_a, \epsilon_p \rightarrow 0$) for the WMPC with $d = 550$ nm (Fig. 3e, f). In order to further comprehend the important role of the natural WVA of Fano resonance, we have shown the comparison of the transmitted TM and TE polarized intensities with TE polarized excitation (Fig. 3c). This clearly shows that the transmitted TM polarized intensity is much weaker than the TE polarization signal and both approach their respective minima in the vicinity of the Fano spectral dip where the rotation reaches its maximum value. This indicates that the amplification of the weak Faraday effect arises due to the near destructive interference of the TE polarized quasiguided mode with the continuum mode at close vicinity of the Fano spectral dip and it takes place at the expense of the total intensity signal, which is a universal signature of WVA. The simulated Faraday rotation ψ and ellipticity ξ for the WMPCs having $d = 550$ nm is also observed to follow the ($\propto \alpha \cot \epsilon_{a/p} \sim \frac{\alpha}{\epsilon_{a/p}}$) behavior (Fig. 3e, f) as predicted by the natural WVA formalism. A quantitative

Fig. 2 The dependence of the enhanced Faraday rotation and ellipticity on the geometrical parameters of the Fano resonant waveguide magneto-plasmonic crystal (WMPC) system with transverse electric (TE) polarized excitation. The finite element method (FEM) simulated transmission spectra, the spectral variation of the Faraday rotation ψ , ellipticity ξ , and the transmitted transverse magnetic (TM) polarization intensities of the WMPC are shown for varying periodicity (d , (a), (b), (c), (d)), width (w , (e), (f), (g), (h)), and height (h , (i), (j), (k), (l)) of the gold (Au) gratings (shown for $E = \hbar\omega = 0.83$ to 2.067 eV), here $\hbar$ is the reduced Planck's constant and ω is the frequency. Prominent signatures of Fano resonance with asymmetric spectral line shape are observed in all the transmission spectra (a, e, i). Large enhancements of the Faraday rotation (b, f, j) and ellipticity (c, g, k) are observed around the Fano spectral dip ($E = \hbar\omega_F$) for all the geometrical parameters. The spectral variation of the transmitted transverse magnetic (TM) polarization intensities (d, h, l) is also shown for each of the varying geometrical parameters of the WMPC. The periodicity (d) parameter of the grating is varied from 400 to 650 nm with a step size of 50 nm, keeping fixed width ($w = 120$ nm) and height ($h = 100$ nm). Similarly, the w parameter of the grating is varied from 80 to 160 nm in a step of 20 nm with a fixed $d = 550$ nm and $h = 100$ nm. The h parameter is increased from 80 to 120 nm with a step of 10 nm for a fixed $d = 550$ nm and $w = 120$ nm. In order to maintain clarity in the figures, the baseline magnitudes of Faraday rotation ψ and ellipticity ξ are shifted by ~ 1.5 deg. consecutively for each sub-plot with varying periodicity, width and height of the Au gratings.

comparison of the amplified Faraday rotation ψ (Fig. 3e) and the ellipticity ξ (Fig. 3f) with the exact theoretical predictions of natural WVA of Faraday effect in Fano resonance (using Eq. S4 and S6 of Supplementary information) shows good agreement. This confirms that natural WVA in Fano resonance is the underlying reason for the enhancement of weak Faraday effect in the WMPC system having a value of periodicity $d = 550$ nm. We now move on to inspect similar results for the WMPC with periodicity $d = 650$ nm (Fig. 3g–l). An important difference between the WMPC with $d = 550$ nm as compared to that with $d = 650$ nm is that while for the former the resonance frequencies

of the TM and TE quasiguided modes perfectly overlaps ($\omega_0^{\text{TE}} = \omega_0^{\text{TM}}$), for the latter these two frequencies are separated ($\omega_0^{\text{TE}} \neq \omega_0^{\text{TM}}$). Consequently, the amplitude and the phase offset weak value parameters $\epsilon_{a/p}$ for the TE and $\epsilon'_{a/p}$ for the TM interfering modes will differ owing to their different resonance frequency. The amplification of Faraday effect will therefore explicitly depend on both set of the amplitude and the phase offset parameters, $\epsilon_{a/p}$ and $\epsilon'_{a/p}$. These offset parameters corresponding to the TE and TM waveguide modes are shown in Fig. 3i, j, respectively. From the presented results (Fig. 3i, j) it is

Periodicity 550 nm

Periodicity 650 nm

evident that both set of the offset parameters $\epsilon_{a/p}$ and $\epsilon'_{a/p}$ do not simultaneously approach zero at any frequency around the Fano spectral dip ω_F , which is desirable for optimal WVA of Faraday effect. Hence the maximum achievable amplification of both the Faraday rotation and ellipticity gets limited with increasing difference between ω_0^{TE} and ω_0^{TM} . In contrast, when the resonance frequencies are same for both the TE and the TM waveguide modes ($\omega_0^{\text{TE}} = \omega_0^{\text{TM}} = \omega_0$), one obtains the ideal WVA scenario around the Fano spectral dip, which leads to maximum enhancement of the Faraday effect. This indeed is the case as the enhancement of both the Faraday rotation (Fig. 3g)

and ellipticity (Fig. 3h) are considerably weaker for the WMPCS with $d = 650$ nm as compared to that for $d = 550$ nm (Fig. 3a, b). Note that in such case also, even though the exact theoretical predictions of natural WVA of Faraday effect in Fano resonance marginally deviates from the observed Faraday rotation ψ (Fig. 3k) and ellipticity ξ (Fig. 3l), it still provides reasonable agreement.

To summarize, the results presented in Figs. 2 and 3 provide conclusive evidence that natural WVA of Faraday effect in the spectral domain interference of Fano resonance is the primary mechanisms for the enhancement of Faraday rotation and ellipticity in WMPCS with TE polarization excitation. Moreover,

Fig. 3 Interpretation of enhanced Faraday rotation and ellipticity of waveguide magneto-plasmonic crystal (WMPC) for transverse electric (TE) polarized excitation through natural weak value amplification (WVA) of Faraday effect in Fano resonance. The simulation results are shown for two different periodicities (d) of the grating in the WMPC: (a–f) $d = 550$ nm and (g–l) $d = 650$ nm. The spectral variations ($E = \hbar\omega = 0.83$ to 2.067 eV) (here $\hbar$ is the reduced Planck's constant and ω is the frequency) of Faraday rotation ψ (right axis, red solid line) (a, g) and ellipticity ξ (right axis, red solid line) (b, h) are shown along with the transmitted intensity profiles (left axis blue solid line) and the bare film Faraday rotation (left axis red dotted line). In the inset of Fig. 3a, the spectral variation of the magneto-optical figure of merit (MOFOM) of the WMPC system (pink solid line) is shown around the Fano spectral dip region and compared with that of the bare film (pink dotted line). c A comparison of the transmitted transverse magnetic (TM) (right axis red solid line) and TE polarized intensities (left axis blue solid line) for TE polarized excitation. d, i, and j Spectral variations of the weak measurement parameters, amplitude offset ϵ_a (left axis, blue solid line) and the phase offset ϵ_p (right axis, red solid line) around the Fano spectral dip ($E = \hbar\omega_f$) for both the waveguide modes. e and k The variation of the Faraday rotation ψ as a function of amplitude offset parameters ϵ_a of TE and ϵ'_a of TM waveguide modes (gray metallic balls) and the corresponding theoretical predictions of natural WVA (red solid line) (using Eqs. S4–S6 of supplementary information). The ϵ_a and ϵ'_a parameters are shown in the lower and upper X-axes, respectively. f and l The variation of the ellipticity ξ as a function of the phase offset parameters ϵ_p of TE and ϵ'_p of TM waveguide modes (gray metallic balls) and the corresponding theoretical predictions of natural WVA (red solid line) (using Eq. S4–S6 of Supplementary information). The ϵ_p and ϵ'_p parameters are shown in the lower and upper X-axes, respectively.

strong spectral overlap between the TM (x) and the TE (y) quasiguided resonance modes provides an ideal setting for natural WVA in Fano resonance, which leads to achieve an optimal enhancement of Faraday rotation and ellipticity in the WMPCs. It is also important to note that the WVA approximation does not break down even if the resonance modes are spectral away from each other, only the magnitude of amplification decreases with slight deviation from the ideal WVA behavior that is known to be more accurate for small magnitudes of the amplitude and the phase offset parameters. Therefore, it may be logical to conclude that in this case, the same mechanism of natural WVA works even if the resonance frequencies of the two modes are not the same.

It is pertinent to note here that, the amplification of any weak effect within the framework of WVA always takes place at the cost of the total intensity signal. Despite the loss of the signal, it has been well demonstrated^{15–17,19} that WVA leads to significant enhancement of actual signal to noise ratio as it throws away redundant signal and picks up only the relevant part of the signal responsible for the amplification effect. The enhancement of Faraday rotation in our WMPC system with TE polarization excitation is no exception in this regard. Like other usual optimization strategy of WVA, here also optimal amplification of Faraday effect and moderate transmittance can be obtained simultaneously by carefully choosing a frequency window around the Fano spectral dip (see Supplementary Note 2 for details). Note that for photonic device applications, it is desirable to have simultaneous enhancement of both the optical transmission and the Faraday rotation angle. In order to evaluate the practical performance of a MO device, the magneto-optical figure of merit (MOFOM) is usually defined as $\text{MOFOM} = (|\theta| \times \sqrt{T})$, where θ is the Faraday rotation angle and T is the transmittance coefficient⁴. In the inset of Fig. 3a, we have therefore shown the spectral variation of the MOFOM of the WMPC system around the Fano spectral dip (in the region of interest) and compared it with that of the bare film. This figure clearly highlights the advantage of using the WMPC system and provides evidence that the WMPC system is a potential candidate for building nonreciprocal photonic devices. It is also important to note in this regard that in all realistic optical Fano resonant systems (like the WMPC), the scattered intensity never reaches zero at the Fano spectral dip due to the presence of finite dissipation in practical systems. This may also therefore enable one to work even at the exact Fano dip, where the maximum amplification can be utilized. We now turn our attention to the enhancement of Faraday effect in WMPCs with the TM polarization excitation, where the surface plasmons are directly excited and hence the underlying mechanism is expected to be fundamentally different and more complex.

Enhancement of MO effects in WMPCs for TM polarization excitation: role of the waveguide-plasmon strong coupling and avoided crossing. With the TM polarization excitation, the spectrally narrow quasiguided mode and the broad surface plasmon modes are simultaneously excited, which leads to hybridization and strong coupling of the waveguide-plasmon modes. As a result of this, the waveguide-plasmon hybrid mode splits the resonance and two dips are observed in the transmission spectra ($E = 0.83$ to 2.067 eV) of the WMPC (Fig. 4a, e, i). Even though there is mild spectral asymmetry in the transmission spectra, the Fano resonance is not as prominent as that for the TE polarization excitation. One reason for this is the fact that in case of TE polarization excitation, the photon continuum provides an ideal continuum as desirable for ideal Fano resonance, whereas the broad surface plasmon mode has finite spectral line width. Despite the fact that one has hybridized waveguide-plasmon modes, the dominant contributions of the two different modes in the observed spectral dips can still be distinguished for certain range of the geometrical parameters of the WMPC. For example, at lower value of the periodicity of the grating $d = 400$ nm, the transmission dip at the lower frequency end (energy $E = \hbar\omega \sim 1.38$ eV) shows broader spectral feature which therefore appears to be dominated by the broad surface plasmon mode (Fig. 4a). The sharp waveguide resonance, on the other hand, dominates the behavior of the narrower dip at the higher frequency end ($E \sim 1.91$ eV) (discussed subsequently). With increasing value of the periodicity d of the grating, the two modes (waveguide mode and the plasmon resonance mode) approach spectrally closer to each other and a clear avoided or anti-crossing behavior^{30,31} is observed as a manifestation of the strong coupling phenomenon (Fig. 4a). It is however, important to note that large enhancement of both the Faraday rotation ψ (Fig. 4b) and ellipticity ξ (Fig. 4c) are always observed in the spectral dip at the lower frequency end which is primarily dominated by the surface plasmon mode for lower value of the grating periodicity (below the avoided crossing regime) and is dominated by the waveguide mode at higher grating periodicity (above the avoided crossing). Thus, both the electromagnetic near field enhancement associated with the surface plasmons and the formation of the strongly coupled waveguide-plasmon polariton play important role in this enhancement. A trend similar to that was observed for the TE excitation is also observed here with varying periodicity d of the grating (Fig. 4a, b, c), the magnitudes of the enhanced Faraday rotation ψ (Fig. 4b) and ellipticity ξ (Fig. 4c) attain a maximum value for a specific value of d (500 nm) and then decreases. Here, the maximum enhancement of the rotation ($\psi \sim 1.536^\circ$) and ellipticity ($\xi \sim 2.68^\circ$) are obtained for the range of $d \sim 475$ –550 nm. This is interesting as this periodicity range is exactly within the window of the avoided crossing regime where the splitting is minimum and the two modes are spectrally the closest

Fig. 4 The dependence of the enhanced Faraday rotation and ellipticity on the geometrical parameters of the waveguide magneto-plasmonic crystal (WMPC) system with transverse magnetic (TM) polarized excitation. The finite element method (FEM) simulated transmission spectra, the spectral variation of the Faraday rotation ψ , ellipticity ξ , and the transmitted transverse electric (TE) polarization intensities of the WMPC are shown for varying periodicity (d , **a, b, c, d**), width (w , **e, f, g, h**) and height (h , **i, j, k, l**) of the gold (Au) gratings (shown for $E = \hbar\omega = 0.83$ to 2.067 eV) here $\hbar$ is the reduced Planck's constant and ω is the frequency. Simultaneous excitation of waveguide and plasmon leads to the formation of hybrid plasmon-waveguide modes and consequently two dips appear in the transmission spectra (**a, e, i**). Large enhancements of the Faraday rotation (**b, f, j**) and ellipticity (**c, g, k**) are observed around the transmission dip at the lower frequency end. The spectral variation of the transmitted transverse electric (TE) polarization intensities (**d, h, l**) are also shown for each of the varying geometrical parameters of the WMPC. The periodicity (d) parameter of the grating is varied from 400 to 650 nm with a step size of 50 nm, keeping fixed width ($w = 120$ nm) and height ($h = 100$ nm). Similarly, the w parameter of the grating is varied from 80 to 160 nm in a step of 20 nm with a fixed $d = 550$ nm and $h = 100$ nm. The h parameter is increased from 80 to 120 nm with a step of 10 nm for a fixed $d = 550$ nm and $w = 120$ nm. In order to maintain clarity in the figures, the baselines of each of the spectra are shifted. In order to maintain clarity in the figures, the baseline magnitudes of Faraday rotation ψ and ellipticity ξ are shifted by ~ 1.5 deg. consecutively for each sub-plot with varying periodicity, width and height of the Au gratings.

(shown subsequently). This underscores the important role of the strong coupling and the avoided crossing of the waveguide-plasmon modes in the resulting enhancement of Faraday effect. Note that a very similar trend is also observed for varying width w of the grating in the WMPC (Fig. 4e, f, g). The avoided crossing behavior of the two modes appears in the transmission spectra since the width parameter w changes the spectral position of the plasmon resonance (Fig. 4e). The maximum enhancement of the Faraday rotation (Fig. 4f) and ellipticity (Fig. 4g) are obtained for 120 nm grating width, which is once again within the window of the avoided

crossing regime of minimum spectral splitting. No significant changes in the transmission spectra (Fig. 4i) are observed with the variation of height h of the grating as it neither affects the spectral response of the plasmons nor of the waveguide resonances (Fig. 4i, j, k). For each of the cases of varying periodicity, width and the height of the grating in the WMPCS, the transmitted TE polarization spectra are also shown with TM polarization excitation (Fig. 4, d, h, l).

In order to further comprehend the role of the avoided crossing behavior associated with the strong coupling of the

Fig. 5 Understanding the role of the waveguide-plasmon strong coupling and avoided crossing on enhanced Faraday effect in waveguide magneto-plasmonic crystal (WMPC) system with transverse magnetic (TM) polarized excitation. **a** The frequencies (energy $E = \hbar\omega$) (here $\hbar$ is the reduced Planck's constant and ω is the frequency) corresponding to the spectral dips are shown as a function of varying value of periodicity d of the grating in the WMPC width and height fixed at 120 and 100 nm, respectively. The dispersion of the transverse electric (TE) waveguide mode (black dotted line) is also shown for varying periodicities. The spectral variation ($E = \hbar\omega = 0.83$ to 2.067 eV) of Faraday rotation ψ (**b**, right axis, red solid line) and ellipticity ξ (**c**, right axis, red solid line) for grating periodicity $d = 500$ nm within the window of the avoided crossing. The spectral variation of the transmitted TM polarized intensities are also shown (left axis, blue dashed line). The simulated spatial distribution of the magnetic field (H) for input TM polarization (H_y) at energies (frequencies) corresponding to the two transmission dips are shown for grating period $d = 400$ nm (below the avoided crossing regime) (**d**), for $d = 500$ nm (at the avoided crossing regime) (**e**), and for $d = 650$ nm above the avoided crossing (**f**). The cross section of the WMPC is shown by white solid lines, with the rectangles representing the position of the gold (Au) gratings.

waveguide-plasmon modes, the frequencies (energy $E = \hbar\omega$) corresponding to the two spectral dips are shown as a function of varying magnitudes of periodicity d of the grating in the WMPC (Fig. 5a). A clear avoided crossing behavior is seen and the minimum spectral difference (minimum splitting) between the two branches appears for the grating periodicity $d \sim 475$ – 550 nm, for which the maximum enhancement of the magnitudes of the Faraday rotation ψ (Fig. 5b) and ellipticity ξ (Fig. 5c) are observed. To understand the role of the hybridization of the plasmon and the waveguide modes, the simulated spatial distribution of the magnetic field for input TM polarization (H_y) at frequencies (energies) corresponding to the two transmission dips are shown for three different grating periods. The first one is for grating period $d = 400$ nm (Fig. 5d) below the avoided crossing regime, the second one is for $d = 500$ nm (Fig. 5e) which is exactly at the avoided crossing regime corresponding to the minimum splitting, and the third one is for $d = 650$ nm (Fig. 5f) above the avoided crossing regime. For grating period $d = 400$ nm below the avoided crossing, the field distribution corresponding to the spectral dip at the lower frequency ($E = 1.38$ eV) shows dominant character of plasmon resonance, whereas the waveguide field distribution is better visible at the longer frequency ($E = 1.91$ eV) region (Fig. 5d). Above the avoided crossing of the modes, the nature of the two modes flip, which can be clearly observed from the spatial field distribution for $d = 650$ nm grating period (Fig. 5f). The lower frequency ($E = 1.14$ eV) dip now shows prominent signature of waveguide field distribution and the dip at the higher frequency

($E = 1.46$ eV) is dominated by the plasmon mode. For grating period $d = 500$ nm near the avoided crossing, a stronger hybridization of the waveguide-plasmon mode is observed, where maximum enhancement of the rotation and ellipticity are also observed. Note that the enhancement of Faraday effect is observed in the lower frequency spectral dip in the avoided crossing regime where the electromagnetic field enhancement is maximum (Fig. 5d, e, f). It is also crucial in this regard that in the window of the avoided crossing (at $\sim d = 500$ nm grating periodicity), the plasmon and the waveguide modes are spectrally the nearest to each other leading to the intersection of the TE waveguide mode dispersion curve with the lower frequency dip of the TM-excited hybrid waveguide-plasmon mode (shown in Fig. 5a). This therefore provides an ideal setting for the resonance enhanced cross-coupling between the TM-TE polarizations enabling maximum enhancement of Faraday effect in this region.

Discussion

In summary, our studies have unraveled different physical origins for the enhancement of Faraday rotation and ellipticity in magneto-plasmonic crystals with TE and TM polarization excitation. Natural WVA of weak Faraday effect that arises due to near destructive spectral domain interference in Fano resonance of the plasmonic crystals is identified as the primary mechanisms for enhancement with TE polarization excitation. The results also showed that the enhancement of the MO effects are maximum for those geometrical parameters of plasmonic crystals which exhibit

a strong spectral overlap of the TE and TM quasiguided modes, in which case an ideal WVA takes place. In contrast for TM polarization excitation, electromagnetic near field enhancement associated with the surface plasmons and the strong coupling of the waveguide-plasmon modes plays the dominant role in the Faraday effect enhancement. The enhancement is strongest near the avoided crossing regime where the waveguide-plasmon modes are spectrally the closest and the splitting is the minimum. These results are of both fundamental and applied interests. The quantitative understanding gained on the different physical mechanisms for the enhancement of the MO effects provides a useful recipe and a systematic approach for the optimization of the geometrical parameters of the WMPC towards achieving maximum enhancement of Faraday effects and for controlled tailoring of the MO responses of such hybrid systems. The different mechanisms for the enhancement of MO effects for the TE and the TM polarizations also indicate that the choice of input polarization state may provide an extra degree of freedom to optimally combine the two different mechanisms for the enhancement of MO response of such hybrid magneto-plasmonic systems. These may lead to optimized development of multifunctional nonreciprocal photonic nano-devices which potentially enhance their applications in optical isolation, modulation, rotation, magnetic field sensing, and so on. We also envisage that the understanding of the underlying mechanisms may also open up interesting direction of research. For example, the observed enhanced Faraday effects in the absence of plasmon resonances may open up a new avenue where the “near destructive interferometric origin” of enhancement can be used to observe significant enhancement of Faraday effects in all-dielectric nanostructures. This may be of practical interest as unlike the conventional metal-based magneto-plasmonic systems, these all dielectric hybrid MO systems are expected to have much lesser loss yielding high quality factor resonances for practical applications. Moreover, the interferometric origin of natural WVA of Faraday effect also opens up the possibility of extending the philosophy to other interesting wave phenomena like electromagnetically induced transparency (EIT) and absorption (EIA), extraordinary optical transmission (EOT), which have common origin in fine interference effects. We are currently expanding our investigations in the aforementioned directions.

Methods

Finite element Method (FEM) simulation of the WMPCs. A schematic illustration of the FEM simulation²⁶ of transmission spectra and MO responses of the WMPC is presented in Fig. 1. The WMPC system consists Au grating on top of a thin Y-BIG film with quartz substrate. The MO active Y-BIG film is the waveguiding layer and exhibit Faraday effect in the presence of an external magnetic field. For input TE (y) polarization, the electric field of light is oriented parallel to the axis of the Au grating, whereas for TM (x) polarization, the electric field is perpendicular to the grating (Fig. 1a). All the simulations are performed for normal incidence of light and the thickness of the waveguide layer are kept constant ($t = 150$ nm) (Fig. 1b). The far field optical transmittance spectra ($E = \hbar\omega = 0.83$ to 2.067 eV, corresponding to $\lambda = 1495.78$ to 600.62 nm) and the corresponding spectral dependence of Faraday rotation and ellipticity of the WMPC system are studied by systematically varying the grating periodicity (d), width (w), and height (h). For performing the simulation, we have used a tensorial polarizability or a dielectric tensor which has the form

$$\epsilon = \begin{pmatrix} \epsilon_{xx} = \epsilon_{11} & -ig & 0 \\ ig & \epsilon_{yy} = \epsilon_{33} & 0 \\ 0 & 0 & \epsilon_{zz} = \epsilon_{22} \end{pmatrix}. \text{ Where the magnetic field induced off-}$$

diagonal elements of ϵ are the characterizing properties of the MO material (Y-BIG) and the origin for Faraday effects. The permittivity tensor elements of the Y-BIG film were taken, $\epsilon_{11} = \epsilon_{33} = 6.7 + 0.053i$ and $g = 0.016 - 0.0092i$ for typical magnetic field of 140 mT³ and dielectric permittivity of Au was taken from literature³². For performing the FEM simulation, the commercial software named COMSOL is used and consequently the conventional sign notation of the dielectric permittivity is used ($\epsilon_{11} = \epsilon_{33} = 6.7 - 0.053i$ and $g = 0.016 + 0.0092i$).

The spectral variations of the Faraday rotation and ellipticity from the transmitted intensity spectra of the WMPC were generated using standard Stokes

polarization method³³. Briefly, for a given input polarization of light (TM-x or TE-y), six different polarization resolved intensity components of the transmitted light were recorded, namely, I_H – horizontal (x) linear polarization, I_V – vertical (y), linear polarization, I_P – 45° linear polarization; I_M – 135° linear polarization; I_R – right circular polarization, I_L – left circular polarization. These intensities were used to yield the spectral variation of the Stokes parameters $[I, Q, U, V]^T$ ³³. The observed net Faraday rotation (defined as polarization vector orientation angle ψ) and net Faraday ellipticity (defined as ξ) are determined from these Stokes parameters of transmitted light³³. Note that the angle ψ is always defined with respect to the input polarization (x or y).

Data availability

The datasets generated during and/or analyzed during the current study are available at Figshare repository. <https://doi.org/10.6084/m9.figshare.14060579.v1>.

Code availability

The computer code or algorithm used to generate the data presented in the manuscript are available from the corresponding author on reasonable request.

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Author contributions

J.K.N. and S.G. contributed equally to this work. S.G. and J.K.N. performed all the FEM based numerical simulations of polarization resolved transmission spectra from the WMPCs, analyzed data, contributed in theoretical modeling and in writing the manuscript. A.K.S. contributed in theoretical modeling and in data analysis. N.G. designed and supervised this study, contributed in theoretical modeling, analysis/interpretation of the results and in writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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