Selective electric and magnetic sensitivity of aperture probes

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Abstract: We report the effect of geometrical factors governing the polarization profiles of near-field scanning optical microscope (NSOM) probes. The most important physical parameter controlling the selective electric or magnetic field sensitivity is found to be the width of the metal rim surrounding aperture. Probes with metal rim width $w < \lambda/2$ selectively senses the optical electric field, while those with $w > \lambda/2$ selectively senses the optical magnetic field. Intensity variation of optical Hertz standing wave formed upon reflection at oblique incidence shows a phase difference of $\pi/2$ between electric and magnetic probes: an analogue of the classical Wiener’s experiment. Our work paves way towards electromagnetic engineering of nanostructures.

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1. Introduction

Optical magnetic field interaction with matter has often been ignored, as summarized by the unity magnetic permeability [1]. Mounting experimental results [1–15] are witnessing that such assumption doesn’t always hold, especially in subwavelength nanostructures where drastic change of spatial electric field distribution and carefully designed closed current loops enhances the magnetic field [18–27]. With advances in nanofabrication technologies and computation methods, nanostructures with effective non-unity magnetic permeability in optical frequency becomes readily available [28]. Using materials with tuned magnetic response at optical frequency perfect lens by negative refraction [29], controlled transmission through nanohole [30] and optical clocking can be achieved [31]. Possibility of sensing and...
enhancement of optical magnetic field [32] and magnetic plasmons propagation [27] has been demonstrated using fabricated nanostructures. Experiments in this direction has demonstrated controlled directionality, polarization and spontaneous emission spectrum using differences between the local density of states between electric dipole and magnetic dipole for optical switching applications [33, 34]. Enhanced non-linear optical effects have been observed in the vicinity of magnetic dipolar resonances [27].

However, design and optimization of optical magnetic field sensitive metamaterials needs heavy computational work partly due to lack of reliable methods to access local optical magnetic field. Only recently, local optical magnetic field becomes experimentally measurable using near-field scanning optical microscopy (NSOM) [10, 11, 35–39]. Although probes with optical magnetic field sensitivity were observed, but probes with controlled optical electric and magnetic field sensitivity had not been realized prior to this work [2, 10, 11]. The ability to independently map electric and magnetic field in nanostructures would bring the metamaterials research to a new height.

Here we report on what physical factors govern selective sensitivity of apertured metal coated NSOM probes to either optical electric or magnetic field. The selective electromagnetic field sensitivity is primarily decided by the metal rim width. The physics lies in the lambda-zone: when the thickness of the metal is larger than $\lambda/2$, the probe is magnetic; when it is less, it becomes electric. Essentially, the finite speed of light guarantees that anything larger than $\lambda/2$ can be considered infinite, bringing the probe into the Bethe hole regime- a single hole lying on an infinite plane. As a proof of principle measurement, an analogue of classical Wiener's experiment ascertains one's freedom to tune NSOM tips to independently map electric and magnetic fields.

2. Results and discussions

We fabricated tapered optical fibers of various diameters by fusion splicing single mode optical fiber (Thorlabs 780HP - 780 - 970 nm with Ø125 µm cladding) with commercial CO₂ laser splicing machine (P-2000, Shutter Instrument) and coated with varying width of aluminum layer using thermal evaporation. For uniform metal coating we had used tilted fiber mount 30° inclined with respect to the horizontal on a rotating stage. Adhesion of aluminum to glass was enhanced using 5 nm layer of chromium deposited using e-beam evaporation. The fabricated probes were milled using focused ion beam (Model No. Quanta 3D (FEI)) to achieve nearly flat bottom with different aperture size by orienting probe axis perpendicular to the ion-beam direction. The desired aperture size a (nm) is controlled by position of the milling from tip apex, while the metal rim width w (nm) is controlled by amount of metal evaporated. Using light at oblique incidence angles ($\theta = 72^\circ$), the effect of incident electric ($\vec{E}_i$) and magnetic field ($\vec{H}_i$) components projected onto the reflecting plane ($\vec{E}_r$ and $\vec{H}_r$) on scattering polarization was monitored to access the selective electric and magnetic field sensitivity of the NSOM probes. We measured scattering of light of wavelength 788 nm through NSOM probes to access their selective EM field sensitivity layout shown in Fig. 1(a).

The direction of the incident polarization ($\phi$) was varied monotonically using $\lambda/2$-wave plate. Direction and intensity of the scattered field was measured by using analyzer and Avalanche photo-diode (SPCM-AQR-16) coupled to photon counter from Stanford research systems (SR400 - Gated photon counter 2 channel). The $\lambda/2$-wave plate and analyzer was precisely rotated using Thorlabs 3-axis piezo controller (Thorlabs - MDT693A). Analyzer was rotated from 0 to 360° in steps of 2° to measure the scattered radiation lobe. The direction of scattered polarization is decided by maximum intensity points of radiation lobe. Oblique incidence with asymmetric polarization ($0 < \phi < 90^\circ$) states on the metal plane enable separate quantification of effect of electric and magnetic fields on NSOM probes.
Fig. 1. (a) Shows layout of the experiment at oblique incidence ($\theta = 72^\circ$) and with arbitrary incident polarization ($\phi$) for probe characterization. $\phi$ is varied using $\lambda/2$ wave plate and the state of the scattered polarization ($\psi_s$) is analyzed using linear polarizer. The polarization direction of the scattered light is indicated by maxima of the polar plot. (b) and (c) are the polar plots of variation of scattered intensity for varying incident polarization angle ($\phi$) at two different incidence angles $\theta = 0^\circ$ (normal) and at $\theta = 72^\circ$ (oblique incidence) for Probe-I and Probe-II respectively. The solid arrow indicates direction of incident projected electric field ($\vec{E}$), while the dashed arrow indicates the direction of projected incident magnetic field ($\vec{H}$). For Probe-I, the maxima of collected radiation lobe follows $\vec{E}$; while for Probe-II it follows $\vec{H}$.

Figure 1(b) shows the plots of scattered dipoles for Probe-I with varying incident polarization direction at normal ($\theta = 0^\circ$) and at oblique incidence angle ($\theta = 72^\circ$). At normal incidence angle the direction of scattered dipole is simultaneously parallel to the incident electric field dipole (blue arrow) and perpendicular to the magnetic field dipole (red arrow). The scattered radiation due to oscillating charge i.e incident electric field is always along the electric field direction while, the direction of the emitted radiation due to induced current led magnetic dipole is always perpendicular to magnetic dipole direction. At normal incidence, since the scattered dipole due to incident electric field and magnetic field are in same direction, it is hard to distinguish the source of scattered radiation whether it is due to electric dipole or, pseudo-magnetic dipoles. At large oblique incidence angle, projected component of incident electric dipole ($\vec{E}_i$) and of magnetic dipole ($\vec{H}_i$) onto the aperture apex, no longer remains orthogonal to each other opening up the possibility to distinguish the source of scattered dipole. For Probe-I, at oblique incidence at asymmetric incident polarization states (for $0 < \phi < \pi/2$), the scattered polarization angle $\psi_s$ is smaller than the incident polarization angle ($\phi$). A closer look to the Fig. 1(b) shows that, the scattered polarization follows the projected incident electric field ($\vec{E}_i$). Simultaneously, this probe shows stronger collection intensity for TE polarization ($\phi = 0^\circ$) than the TM polarization ($\phi = 90^\circ$) as represented by larger size of the lobe, and hence are termed as an “Electric NSOM probe”. Figure 1(c) shows the change in the polarization of scattered dipole of Probe-II with change in the incident polarization ($\phi$). For Probe-II (Fig. 1(c)), the polarization orientation of collected scattered radiation is perpendicular to the projected incident magnetic field ($\vec{H}_i$) for all arbitrary polarization directions ($\phi$), consistent with Bethe’s pseudo magnetic dipole behavior. Again, contrary to the Probe-I, Probe-II shows weaker intensity for TE polarized light and stronger intensity for the TM polarized state and, hence Probe-II is “Magnetic NSOM probe".
Fig. 2. (a) and (b) show polar plots of variation of scattered polarization angle ($\psi_s$) with varying $\phi$ for Probe-I and Probe-II, respectively. Solid line represents theoretical fit to the experimental data. $\alpha_n$ and $\beta_n$ are the estimated electric and magnetic field coupling coefficients normalized with condition $\alpha^2 + \beta^2 = 1$ obtained from fitting experimental results of the variation of diffracted field polarization collected through NSOM probes with component of $E_{\text{diff}} = \alpha E_i + \beta (\hat{n} \times \vec{H}_i)$.

(c) Schematic of the field components and parameters used for modelling. Symbols $a$ and $w$ denote the diameter of the dielectric aperture (in nm) and width of the metal coating (in nm). The incident field vectors are represented by $\vec{E}_i$ (blue arrow) and $\vec{H}_i$ (red arrow). The projected component of field vectors are shown by $\vec{E}_t$ (blue arrow) and $\vec{H}_t$ (red arrow). The amplitude and polarization direction of collected light is represented by $E_{\text{diff}}$ and $\psi_s$.

Figures 2(a) and 2(b) shows the variation of angle of polarization for the collected signal $\psi_s$ for Probe-I and Probe-II, respectively, with change in incident polarization $\phi$. We fit our experimental data assuming that the tangential electric field collected by the NSOM probes can in general be written by $\vec{E}_{\text{diff}} = \alpha E_i + \beta (\hat{n} \times \vec{H}_i)$ (Fig. 2(c)); the blue and red arrows represent the incident electric field $\vec{E}_i$ and the incident magnetic field $\vec{H}_i$ respectively. The tangential component of the incident electric field is expressed by $\vec{E}_t = E_i (-\sin \phi \cos \theta, \cos \phi, 0)$ and of tangential magnetic field is given by $\vec{H}_t = \vec{H}_i (-\cos \phi \cos \theta, -\sin \phi, 0)$. The angle between $\vec{E}_t$ and $\vec{H}_t$ is represented by $\psi$. The polarization angle ($\psi_{E_t}$) of tangential electric field and tangential magnetic field ($\psi_{H_t}$) are non-orthogonal, as evident by the expression of angle between them:

$$\psi = \cos^{-1} \left( \frac{\sin \phi}{\sqrt{1 - \cos^2 \phi \sin^2 \theta}} \right) - \cos^{-1} \left( \frac{\cos \phi}{\sqrt{1 - \sin^2 \phi \sin^2 \theta}} \right).$$

The $\psi_{E_t}$ versus $\phi$ curve is fitted with this equation to obtain the values of $\alpha$ and $\beta$. The fitting function used was obtained from the y-component of the diffraction field ($\vec{E}_{\text{diff}}$) as shown below:

$$\psi_{E_{\text{diff}}} = \cos^{-1} \left( \frac{\alpha E_i \cos \psi_{E_t} + \beta H_i \cos \psi_{H_t}}{\sqrt{\left( \alpha E_i \cos \psi_{E_t} + \beta H_i \cos \psi_{H_t} \right)^2 + \left( \alpha E_i \sin \psi_{E_t} + \beta H_i \sin \psi_{H_t} \right)^2}} \right)$$ (1)
where, $\psi_{\text{occl}} = \psi_{\text{cl}} - \pi / 2$.

The theoretical fit to the experimental data is shown by solid line in Fig. 2(a) and Fig. 2(b) for Probe-I and Probe-II. The estimated values of field coupling co-efficients $\alpha$ and $\beta$ are normalized with condition $\alpha^2 + \beta^2 = 1$ and are represented as $\alpha_n$ and $\beta_n$. The dashed red and blue curves indicate the perfect Electric probe ($\alpha = 1; \beta = 0$) and perfect Magnetic probe ($\alpha = 0; \beta = 1$). For Probe-I, the estimated value of normalized electric field coupling co-efficient ($\alpha_n$) is higher than the normalized magnetic field coupling co-efficient ($\beta_n$), reaffirming the selective coupling of electric field to Probe-I ($\frac{\alpha_n}{\beta_n} = 17.49$). In contrast to Probe-I, the normalized magnetic field coupling coefficient ($\beta_n$) for Probe-II is higher than the $\alpha_n$ ($\frac{\alpha_n}{\beta_n} = 0.24$). While predominantly electric or magnetic tips will be highly desirable for investigation of near field phenomena, the capability to engineer them on demand has not been realized [5].

Guided by our previous experimental results that a Bethe hole in an infinite metal plane behaves as polarization analyzer for magnetic field of light [10], we fabricated number of NSOM probes with varying aperture diameter and metal rim width expecting geometrical factors aperture diameter and metal thickness predominantly decides the selective electric or magnetic field sensitivity of probes. The diameter of the aperture $a$ (in nm) is decided by milling position from the probe bottom, while the metal rim width $w$ (in nm) is controlled through the deposited metal width. The polarization characteristics of collected radiation by NSOM probes of different geometrical parameters were studied as shown in Fig. 3(a) and 3(b). Figure 3(a) shows the effect of metal rim width on the collected intensity ratio of TE and TM incident polarizations. The NSOM probes with $w < 400$ nm (i.e $< \lambda/2$) shows TM/TE ratio $\ll 1$ analogous to Probe- I: the electric probe, while probes with $w > 400$ nm (i.e $> \lambda/2$) shows TM/TE ratio $> 1$ similar to magnetic probe: Probe- II. In agreement to this, the induced normalized magnetic dipole coupling constant ($\beta_n$) obtained by fitting the $\psi_\varphi$ versus $\phi$ curve shown in Fig. 3(b), indicates monotonic increase with increasing $w$.

Our results give the specifics of how to make a tip over 90% electric or magnetic; it is a matter of $w$ being larger or smaller than $\lambda/2$. In contrast, selective field sensitivity of NSOM probes is largely insensitive to aperture diameter ($a$), see Fig. 5 (Appendix). The dominant role of $w$ was not considered in [5], leading to the conclusion that in all cases, symmetric metal coated probes of various aperture diameters simultaneously sense the electric and magnetic field [5]. Such general conclusion is in principle not wrong; but to be useful, deciding factors to fabricate probes with predefined field sensitivity must be revealed through experiments.
Fig. 3. (a) Variation of collected intensity ratio of TM and TE polarized incident light for various metal rim width (w) of NSOM probes: a parameter representing change in optical magnetic field sensitivity with metal rim width. (b) Shows change in the normalized electric ($\alpha_n$) and magnetic field coupling coefficient ($\beta_n$) with varying metal rim width (w). For NSOM probes with width $w > 400$ nm, the collected intensity for TM polarization is larger than the TE polarization state. Fig (c) and (d) shows the calculated surface current intensity (shown by color contrast) and direction of current distributions (by white arrow) around a dielectric aperture of size $0.1\lambda$ in metallic NSOM probe of rim width $0.1\lambda$ and $0.5\lambda$ respectively. The projected components of incident electric and magnetic field directions $\vec{E}$ and $\vec{H}$ inside the aperture are indicated by blue and red arrow respectively. The induced surface current, for NSOM probe with metallic rim width $0.1\lambda$ is along the $\vec{E}$ while, for NSOM probe with metallic rim width of $0.5\lambda$, it’s along the $\vec{H}$.

The experimental results are confirmed by finite-difference-time–domain (FDTD) calculations of field and current distributions at the flat bottom surface of a conical metal coated apertured NSOM probe of hole diameter 80 nm ($0.1\lambda$) and having two different $w$ of 80 nm and 400 nm ($0.1\lambda$ and $0.5\lambda$; $\lambda = 800$ nm) as shown in Fig. 3(c) and 3(d) respectively. The height of the conical probe was taken as 4.4 $\mu$m with taper angle 30° with respect to axis of the aperture and simulation was performed for oblique incidence angle ($\theta = 72^\circ$) and for real metal ($\varepsilon = -46.7 + 28.5i$) with low reflection condition at the domain boundary. The directions of incident tangential field vectors, $\vec{E}_t$ and $\vec{H}_t$, are depicted by blue and red arrows respectively. The intensity of the induced surface current distributions $\vec{J}_{tan}$ is represented by color contrast while the direction is indicated by white arrows. For NSOM probe with rim width of $0.1\lambda$, the induced current directions are along the incident electric field direction, representing capacitive coupling of the incident electric field to the NSOM probe aperture as shown in Fig. 3(c). The capacitive coupling of electric field to the NSOM probes with thinner metal rim width leads to selective sensitivity to the incident electric field direction. This is in agreement with our experimental observation of selective electric field sensitivity of NSOM.
probes with thinner metal rim width \((w < 400 \text{ nm})\). This shows that electric field coupling efficiency is dominant for NSOM probes with rim width \(w < 400 \text{ nm}\). Figure 3(d) shows the surface current density induced around the aperture of same diameter \(0.1 \lambda\) but having metal rim width of \(0.5 \lambda\). For such probes, the induced current is mostly aligned normal to the direction of incident magnetic field. This indicates selective sensitivity of large metal rim width probes to the magnetic field. The dominant magnetic field sensitivity of NSOM probes with \(w > \lambda/2\) is indicative of the probe realizing its Bethe limit \([39, 40]\) at the limit of the \(\lambda\)-zone [39].

![Fig. 4. (a) Schematic of experiment to generate Hertz’s standing wave at optical frequency. FESEM images of probe-I is shown in fig (b). The collection and scattering measurement of the vertical standing wave using Probe-I: the Electric probe using dual mode NSOM setup is shown in fig (c). Fig. (d) shows FESEM image of probe-II: the magnetic probe and the collection and scattering measurement of the vertical standing wave by this probe using dual mode NSOM setup is shown in Fig. (e). Phase difference of \(\pi/2\) between collected and scattered signals from magnetic probes affirms the selective field sensitivity of NSOM probes.](image)

The functionality of electric and magnetic NSOM probes was finally affirmed by mapping the field vector components of a \(z\)-standing wave. The interference of incident wave and reflected wave generates standing wave pattern of both fields in vertical direction schematically shown in Fig. 4(a). Analogous to Wiener’s experiment, using our selective probes we mapped uniquely the electric and magnetic field maxima located out of synch in space. Otto Wiener’s in (1890) successfully mapped the nodes and antinodes of electric field of Hertz standing waves at visible frequency using photographic plates exposed to standing wave formed upon reflection [41]. For standing wave formed upon reflection from metal film, electric field maxima is expected at heights odd multiple of \(\lambda_z/2 = \lambda/(2\cos \theta)\), while magnetic field maxima are shifted in phase by \(\pi/2\). We measured collection signal and scattering signal simultaneously using dual mode NSOM \([42]\) with the electric and magnetic probes, at an incident angle of \(45^\circ\). The scattering signal serves as a reference; the scattering process by probe apex is mainly caused by the electric field. Figure 4(b) shows the FESEM image of Probe-I: the Electric probe. Figure 4(c) plots the \(z\)-dependence of collection and scattering signals from the electric probe and they are completely in phase. FESEM of Probe-II: the Magnetic probe used is shown in Fig. 4(d). For the magnetic probes, the relative phase difference between two signals is \(\pi/2\) (out-of-phase). These results show the possibility of selective detection of electric field and magnetic field with the electric probes and the magnetic probes in random distribution of electromagnetic fields.

3. Conclusions

In conclusion, metallic rim width decides the nature of electromagnetic radiation collected through metal coated sub-wavelength apertured dielectric probes, whether it is electric or,
magnetic field. NSOM probes with metallic width $w < 400$ nm ($< \lambda/2$) primarily collects the electric field, while the probes with thick flat bottom collects dominantly the Bethe’s pseudo-magnetic dipole. Our experimental observations are explained in terms of capacitive coupling of the electric dipole for electric probes and in terms of eddy currents within $\lambda$-zone for magnetic probes and results are in agreement with FDTD simulations. These results establish the method of fabrication of NSOM probes sensitive to magnetic field direction independent of the electric field direction and vice versa. Measurements using these selective field sensitive NSOM probes using simultaneous scattering and collection mode NSOM provide experimental evidence of separate electric and magnetic Hertz standing waves at visible frequency.

Appendix A: Effect of aperture diameter ($a$)

The variation of intensity ratio of collected light using NSOM probes of various aperture size $a$ (in nm) for TM and TE polarization states ($I_{TM} / I_{TE}$) is shown in Fig. 5. Apparently, the selective field sensitivity is largely independent of the aperture diameter (in the range 80 to 400 nm).

![Intensity ratio ($I_{TM}/I_{TE}$) vs. Aperture diameter $a$ (in nm)](image)

Fig. 5. Variation of $I_{TM}/I_{TE}$ intensity ratio with aperture diameter $a$ (in nm). $I_{TM}/I_{TE}$ intensity is largely insensitive to the aperture diameter.

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