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ABSTRACT

In the recent decade metamaterials with magnetic permeability different than unity and unusual response to the magnetic field of incident light have been intensively explored. Existence of magnetic artificial materials created an interest in a scanning near-field magnetic microscope for studies of magnetic responses of subwavelength elementary cells of those metamaterials. We present a method of measuring magnetic responses of such elementary cells within a wide range of optical frequencies with single probes of two types. The first type probe is made of a tapered silica fiber with radial metal stripes separated by equidistant slits of constant angular width. The second type probe is similar to metal coated, corrugated, tapered fiber apertured SNOM probe, but in this case corrugations are radially oriented. Both types of probes have internal illumination with azimuthally polarized light. In the near-field they concentrate into a subwavelength spot the longitudinal magnetic field component which is much stronger than the perpendicular electric one.

Keywords: optical magnetism, plasmonics, magnetic metamaterials, scanning near-field magnetic microscopy, corrugated SNOM probes.

1. INTRODUCTION

Pendry et al. [1] have shown that artificial materials composed of elementary cells fabricated from nonmagnetic conducting elements have effective magnetic permeability different from unity. Urzhumov and Shvets [2] presented theoretical formulas for the frequencies and strengths of electric and magnetic resonances valid for any periodic metallodielectric nanostructures operating in the plasmonic regime. More recently, Merlin [3] considered a metamaterial composed of split rings and spherical inclusions. He showed that if a metamaterial is made of substances with the $\mathrm{Im}|\sqrt{\varepsilon_m}|>>\lambda/d$, where ε_m is the complex permittivity of the metamaterial elementary cell and $\lambda>>d$ is the wavelength in vacuum and d is the characteristic length of the cells, then strong diamagnetic or paramagnetic behaviour characterized by susceptibilities whose magnitude is significantly larger than that of natural substances is possible. According to Merlin, the strength of magnetic effects diminishes with decreasing wavelength. Existence of metamaterials composed of subwavelength elementary cells made of materials with large values of the permittivity creates a need for an analogue of a scanning near-field optical microscope (SNOM) where in search of a magnetic response the cell is illuminated with a concentrated longitudinal component of magnetic field of electromagnetic wave.

The idea of scanning near-field magnetic microscope (SNMM) can be realized in different ways. In the inverse transmission mode of work of SNOM the probe does not serve as a source of evanescent optical field but as a local detector of light. Using this mode of work Devaux et al. [4] observed that the fully dielectric tapered probe collects a signal proportional to the square modulus of the electric near field, while the tapered gold-coated 'display the same patterns as the theoretical maps of the square modulus of the magnetic field associated with the optical near field.' Burresi et al. [5] have reported on SNOM detection of the near-field magnetic component of light in phase-sensitive heterodyne scheme, where signal from an aperture regular probe is combined with that from a probe with split ring resonator (SRR) in the aperture plane. Aperture probes without an SRR at the tip end were used for passive measurements of the magnetic component of modes excited in photonic crystal cavities coupled to waveguides [6-7]. Banzer et al. [8] proposed an optical set-up for testing electric and magnetic properties of single sub-wavelength nanostructures. As an example, the electric and magnetic resonances of a properly oriented SRR were independently measured by means of a y-polarized TEM_{10} mode (y-polarized HG_{01} mode) with a strongly focused on-axis longitudinal magnetic field H_z and off-axis E_y components.

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Recently, Kihm et al. [9] attracted attention to the fact that when a single subwavelength aperture in a metal plane is illuminated with linearly polarized light at an oblique incidence then the surface electric field and surface current are mostly induced by the incident magnetic component of electromagnetic field. Thus, normal-angle scattering from a subwavelength aperture is governed by the magnetic field component of light and thus the aperture acts as a polarization analyser for magnetic vector field.

In this technical note we present two types of tapered along the z direction dielectric probes with discrete [10, 11] or continuous metal coating which concentrate longitudinal magnetic field of light in the near field of their apexes. Cross sections of the probes are shown in Figure 1(left) and (right) – the larger pictures show the xy plane cross sections far away from the apex, while the smaller ones at the apex. The probes have internal azimuthally polarized illumination coupled to plasmons due to momentum matching on radial gratings. The gratings have continuously changing period what allows for efficient coupling within a wide spectral range. Plasmons with a strong azimuthal component propagate towards the apex where they form an azimuthal current in the metal which results in generation of a strong longitudinal magnetic field Hz.

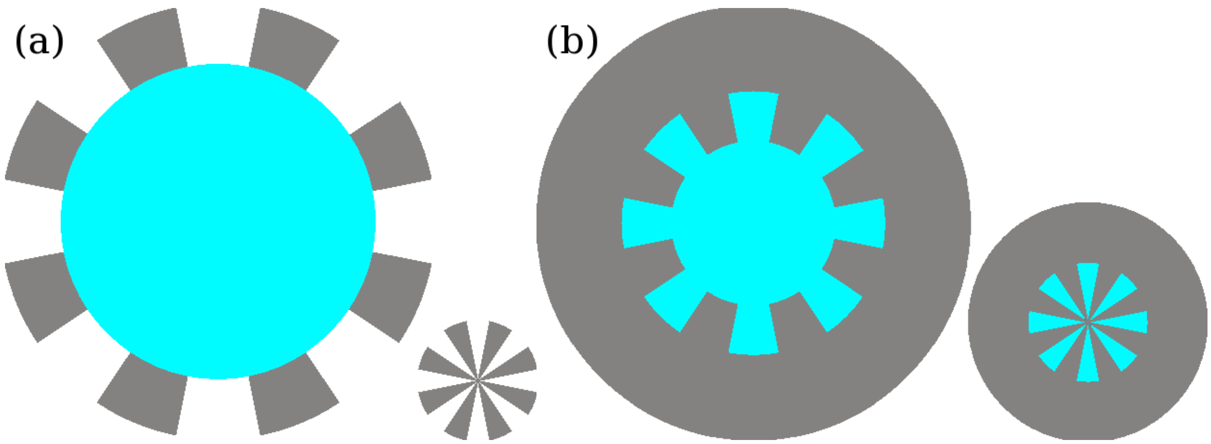

Figure 1. (left) Cross sections of dielectric probe with metal stripes: large graphic shows a cross section far from the apex, small: at apex. The metal thickness of the metal stripes is constant. (right) Cross sections of metal-coated dielectric probe with radial groves: large graphic shows a xross section far from the apex; small at apex. The metal coating thickness as well as groove depth are constant.

Recently, in an effort to find an easy method to fabricate magnetic field concentrators other geometries were proposed [12]. Lee et al. [12] use external illumination and grating-coupling to surface plasmons onto metallic tips. Concentration of H_{apex}-field and at the same time strong suppression of E_z-field is achieved for double-sided illumination in the the H-symmetric (E out-of-phase, H in-phase) or E-antisymmetric (E field out-of phase, H field in-phase) surface plasmon excitation schemes.

2. TAPERED DIELECTRIC PROBES WITH RADIAL STRIPES

Magnetic concentrators of the first type are made of dielectric nondispersive fibers with core diameter equal 3.2 μm which taper smoothly from their regular diameter to the apex. In the simulations we accept a taper half-angle equal to 40°. The metal lands and the slits have constant angular width equal π/8 (eight periods total). The metal lands are made of Ag or Al with thicknesses h varied from 0 to 100 nm. They are modeled using Drude dispersion $\varepsilon(\omega) = \varepsilon_\infty - \omega^2_p/[\omega(\omega + i\Gamma)]$ fitted to experiental data obtained by Johnson and Christy [13] for Ag with parameters equal $\varepsilon_\infty = 3.70$, $\omega_p = 13673$ THz, and $\Gamma = 27.35$ THz. For Al we use data from Ordal et al. [14] with fitting parameters $\varepsilon_\infty = 4.39$, $\omega_p = 12062$ THz, and $\Gamma = 1009$ THz.

Figures 2 and 3 show full-width at half-maximum (FWHM) of the longitudinal magnetic field component Hz calculated 10 nm from the apexes of probes with Ag and Al stripes, respectively. In both cases the stripe thickness changes from 0 to 100 nm. For the largest thickness considered FWHM values are better than half a wavelength. In the case of thin metal stripes plasmons radiate into an azimuthally polarized beam before reaching the apex and diffraction enlarges the spot size considerably. In the whole range of wavelengths FWHM values available with Al stripes monotonically grow with increasing wavelength. This regularity suggest that aluminum is a better choice for stripe metal than silver.

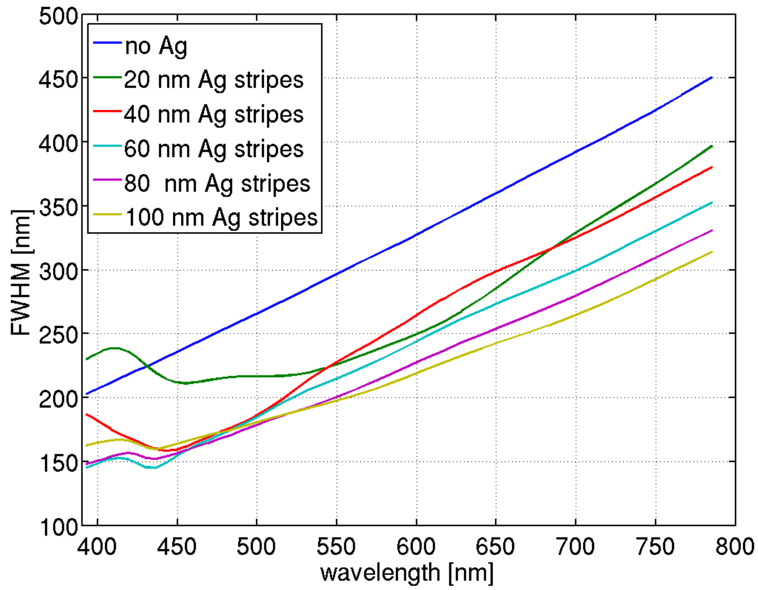

Figure 2. Full-width at half-maximum of the longitudinal field component Hz calculated 10 nm from the apex of a dielectric probe with silver stripes.

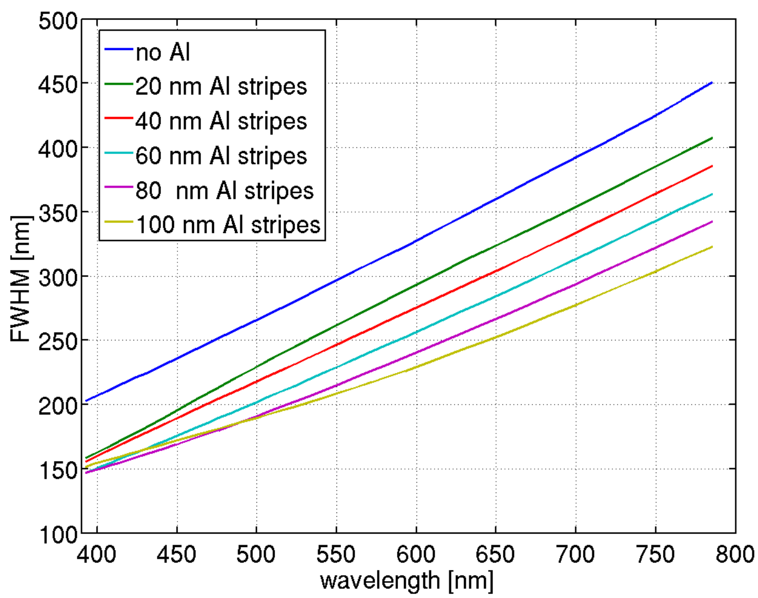

Figure 3. Full-width at half-maximum of the longitudinal field component Hz calculated 10 nm from the apex of a dielectric probe with aluminum stripes.

In near-field of probe apexes not only the longitudinal, accumulated at the z-axis, component of magnetic field is present but also an azimuthal component of the electric field with its energy density increasing away from the z-axis. Figures 4 and 5 present a ratio of magnetic energy density of Hz and electric energy density of Eφ integrated over an area of diameter equal to the FWHM of Hz for Ag and Al probes, respectively. In probes with silver stripes this magnetic-to-electric energy density ratio is higher than in those with Al stripes. It is because a narrow Hz needle is generated by azimuthal currents Jφ flowing through the set of stripes and virtual displacement currents in grooves. Those currents are larger in silver which is less lossy than aluminum. For both metals the optimum stripe thickness is within the range from 40 to 100 nm.

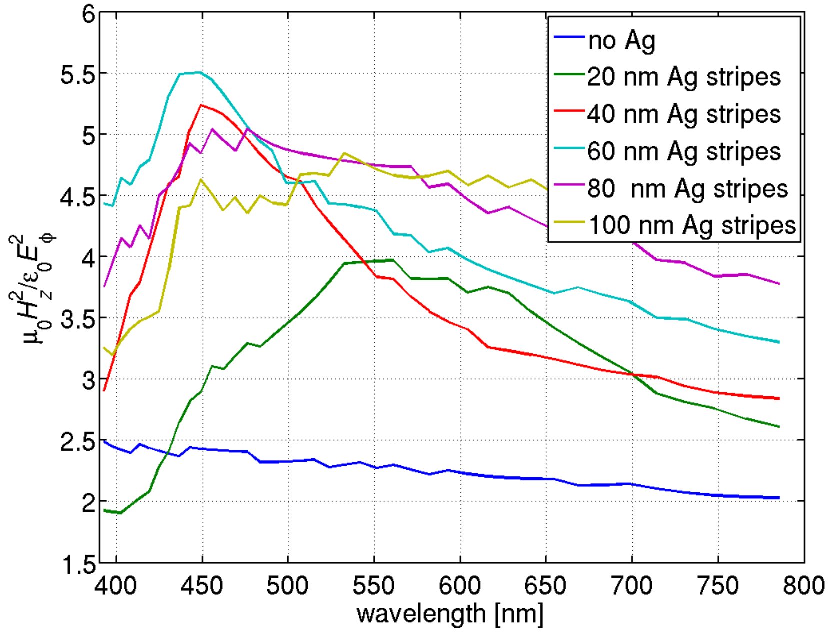

Figure 4. Ratio of magnetic energy density of Hz to electric energy density of Eφ integrated over an area of diameter equal to the FWHM of Hz for dielectric probes with silver stripes.

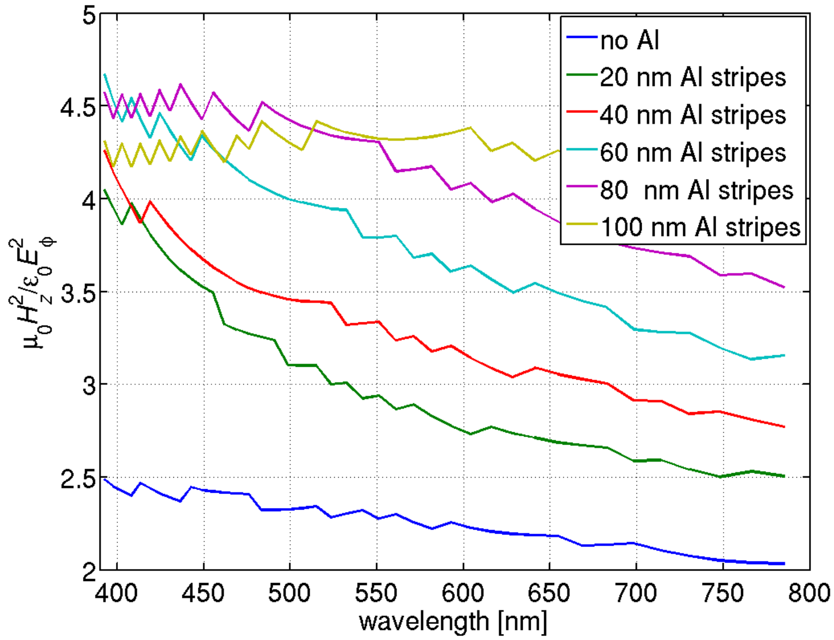

Figure 5. Ratio of magnetic energy density of Hz to electric energy density of Eφ integrated over an area of diameter equal to the FWHM of Hz for dielectric probes with silver stripes.

Fabrication of probes with radial metal stripes completely separated by narrowing along the probes grooves is not an easy task and makes use of focused ion beam etching. Below we propose another geometry of a concentrator of longitudinal magnetic field component of light.

3. TAPERED DIELECTRIC METAL COATED RADIALLY CORRUGATED PROBE

Currently we fabricate SNOM probes in the form of apertured metal-coated tapered fibers where light propagating in the fiber core is coupled to surface plasmons on corrugated core-metal coating interface [15]. When corrugations are made on the tapered fibre surface along the z axis, in simulations we use internal linearly polarized illumination what reduces the problem to two dimensions [16-18]. Real probes have internal illumination with radial polarisation.

The longitudinal magnetic field component Hz can be generated with azimuthal current Jφ on the edge of continuous metal coating at the apex of aperture probe. This is possible when internal azimuthally polarized illumination is coupled to plasmons on core-metal coating interface with corrugations along the angular coordinate (Figure 1b). Simulated performance of such a probe with Al coating in presented in Figures 6 and 7. FWHM of the longitudinal magnetic field component Hz calculated 10 nm from the apex becomes narrower than that of uncorrugated probes for grooves 40 nm deep and more. In comparison with results shown in Figures 2 and 3 the radially corrugated probes gives better FWHM values especially for short wavelengths. Figure 7 shows that ratio of magnetic energy density of Hz to electric energy density of Eφ integrated over an area of diameter equal to the FWHM of Hz is is virtually independent on depth of grooves. The ratio reaches values one order of magnitude bigger than those possible with probes with radial stripes.

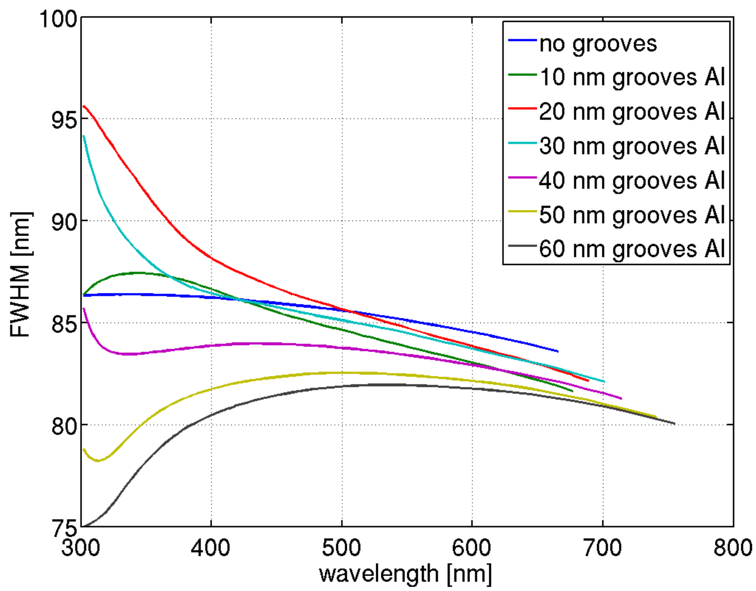

Figure 6. Full-width at half-maximum of the longitudinal field component Hz calculated 10 nm from the apex of a dielectric probe with silver stripes.

4. CONCLUSIONS

An advantage of the proposed magnetic field concentrator is that it may be employed as a scanning near-field probe with shear force control of the probe-sample distance. This distance of single tens of nanometers allows for illumination of individual elementary cells of an arrayed metamaterial. Linear dimensions of those cells should be slightly smaller than FWHM values 160 nm and 80 nm achievable for dielectric probes with radial metal stripes and dielectric probes with continuous metal coating and radial corrugations, respectively. Near-field illumination excites resonances in an elementary cell and |E|2 of scattered light is recorded with a square detector in the far-field.

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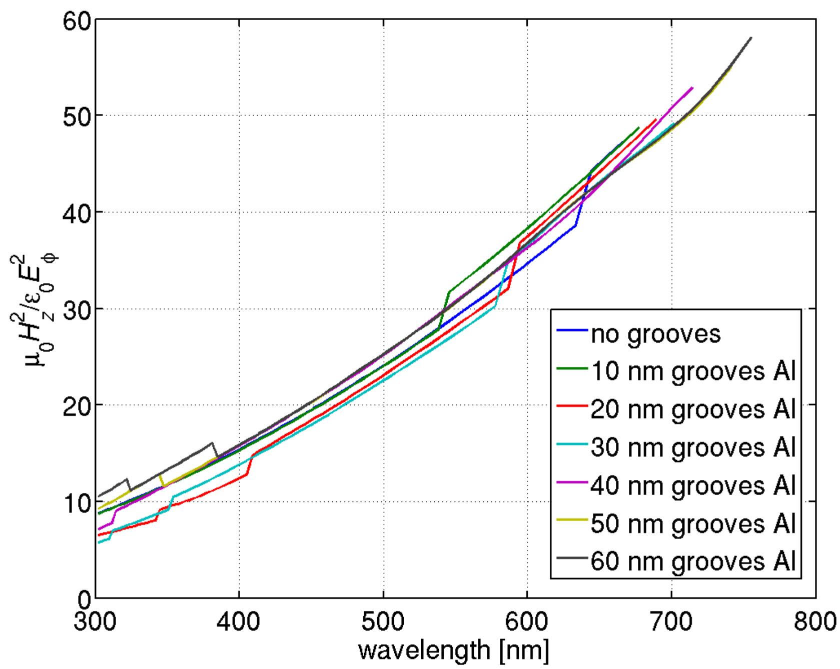

Figure 7 Ratio of magnetic energy density of Hz to electric energy density of Eφ integrated over an area of diameter equal to the FWHM of Hz for dielectric probes with silver stripes.

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