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Enhanced optical transmission by light coaxing: Mechanism of the TEM-mode excitation

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This paper presents a theoretical study showing the mechanism of light transmission through opaque metallic films perforated with nanocoaxial apertures thanks to the excitation of their cutoff-free TEM (Transverse ElectroMagnetic) guided mode. Full three-dimensional Finite Difference Time Domain (3D-FDTD) together with a Body-Of-Revolution FDTD simulation results are presented and discussed in order to optimize this extraordinary transmission. Very promising findings are pointed out opening the path to the design of new devices for both nano-optic and photovoltaic applications.

Extraordinary optical transmission (EOT) has become a well-known phenomenon thanks to extensive theoretical and experimental studies. The EOT accounts for the transmission enhancement of the electromagnetic waves through opaque plates (generally fabricated with metal) perforated with subwavelength apertures. The term EOT is used every time the obtained transmission through the set of apertures is more larger than the sum of the transmission through the apertures considered separately [1]. The origin of the light transmission depends on the considered structure. For 1D periodic slits, the excitation of the TEM guided mode i.e. the mode where the electric field is perpendicular to the slit direction gives rise to large transmission [2] because of the efficient overlap between the incident plane wave and this mode. This TEM mode does not have a cutoff frequency and the transmission peak position is given by a phase matching resonance condition. The drawback of such structures is their polarization sensitivity. In fact, only the electric field component that is perpendicular to the slit direction can be transmitted through the structure acting exactly like a polarizer.

In order to enhance the transmission independently of the polarization, one can consider cylindrical aperture arrays. In this case, an increased transmission is obtained for wavelengths corresponding to the excitation of surface plasmon resonances of the metal-dielectric interfaces [3,4]. Consequently, the transmission

peak position is directly related to the grating period through a simple equation. In addition to the polarization, this kind of structures are also sensitive to the angle of incidence because of the surface plasmon excitation.

In order to combine the advantage of these two structures (slits and cylindrical apertures), annular aperture arrays (AAA) were proposed [5,6], theoretically studied [7–11] and characterized [12–16] over a large interval of the electromagnetic spectrum (see Fig. 1). In all these studies, the EOT is associated with the excitation, inside the apertures, of the TE_{11} mode which has a cutoff wavelength. The excitation of the annular apertures TEM mode was firstly proposed in Ref. [5]. Only few papers have discussed on this mode [17,18] while its excitation conditions were recently pointed out in Ref. [19]. In this letter, we discuss the potential role of this mode in the context of the EOT.

As mentioned above, in the case of AAA, the EOT can be efficiently obtained thanks to the two higher guided modes namely the TEM and the TE_{11} modes. Historically, and due to symmetry considerations, EOT was firstly demonstrated (theoretically and experimentally) by exciting the TE_{11} mode at its cutoff wavelength [13,14,20]. On the other hand, it was demonstrated that the TEM mode, which has no cutoff frequency, can only be excited with an incident plane wave under two conditions: an off-normal incidence (wavevector not collinear with the symmetry-axis of the waveguide) and a TM polarization [19].

EOT in which the TEM mode is excited displays new characteristics. One of the most important properties of the TE_{11} mode is the fact that it is the “higher” guided mode that has a cutoff

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Fig. 1. Schematic of a conventional annular aperture array (AAA) structure. R_o is the outer radius, R_i is the inner one, p is the period and θ is the angle of incidence.

frequency. When illuminating the AAA structure by a plane wave (independently of the incidence direction), the transmission spectrum always presents a peak at the cutoff wavelength of the TE_{11} mode [21]. In addition, if the metal is thick enough, Fabry–Pérot harmonics of this mode appear (see Fig. 3 of Ref. [5]). The existence of a cutoff frequency insures the presence of EOT at this frequency as long as it is not disturbed by Rayleigh or Wood anomalies. Unfortunately, the TEM-based EOT can only be obtained for thick metal plates. In fact, the wavelengths of the transmission peaks are only given by a phase matching condition that can be written as:

$$\lambda_{\text{TEM}} = \frac{2\pi n'_{\text{eff}} H}{m\pi - \phi_r} \quad (1)$$

where n'_{eff} is the real part of the effective index of the TEM mode, ϕ_r is the phase change induced by the reflection on the two ends of the coaxial waveguide, H is the metal film thickness and m is an integer. Note that both n'_{eff} and ϕ_r depend on the wavelength value. Consequently, similarly to a conventional Fabry–Pérot interferometer, by changing H , it is possible to tune the value of the transmitted light wavelength. Thus, the question is: can we obtain more efficient EOT through the TEM mode than with the TE_{11} one? The answer is not obvious because, in addition to the geometrical parameters, the metal dispersion (more precisely the absorption) plays a key role in the determination of the transmission at a given wavelength. For an AAA made in a perfect electric conductor (PEC), the response of the above question becomes simpler. A PEC is an ideal material without losses and with an infinite conductivity. In this case, the absence of the absorption allows the presence of an efficient TEM peak at oblique incidence for a given value of the wavelength by adjusting the metal film thickness. This becomes dramatically difficult in the case of a real metal with absorption especially in the visible range. In this case, both real and imaginary parts of the effective index of the TEM-like mode depend on the nano-waveguide radii (see Fig. 2). Therefore, in order to optimize the light transmission through an AAA thanks to a TEM mode, we have to optimize the transmitted efficiency by determining all the structure parameters including the optical parameters of the used metal.

Fig. 3 shows the transmission spectra of a perfectly symmetrical AAA (perfect conductor in (a) and silver [27] in (b)) illuminated with a TM polarized plane wave impinging on the structure at $\theta = 45^\circ$. The geometrical parameters of the considered structures are given in the caption of the same figure. One can conclude that the appearance and the position of the TEM peak transmission are directly related to the metal thickness.

In addition, one notices that, even if the imaginary part of the TEM mode effective index decreases with increasing wavelength values (see Fig. 4d of Ref. [19]), the height of the TEM peak decreases due to the larger value of the thickness needed to obtain the first harmonic of the Fabry–Pérot resonance inside the apertures. On

Fig. 2. Real part n'_{eff} and $\log_{10}$ of the imaginary part n''_{eff} of the effective index associated with the TEM-like mode of an infinite coaxial waveguide as a function of the outer radius R_o . The inner radius is set to $R_i = 65$ nm and the working wavelength is $\lambda = 1550$ nm.

the other hand, it is clearly seen from the same Fig. 3a and b, that the coupling between the TE_{11} and the TEM modes plays a negative role on the global transmission. The linear behavior obtained elsewhere is completely broken near the coupling zone. Furthermore, the values of the phase shift ϕ_r can be deduced from Fig. 3a and b replacing in Eq. (1) n_{eff} by 1 for a perfect conductor AAA and by 1.35 in the case of silver (deduced from Fig. 2). This leads to almost constant and small values of $\phi_r^{\text{PC}} = 7.34^\circ$ and $\phi_r^{\text{Ag}} = 1.84^\circ$.

From Fig. 3b that corresponds to a silver AAA, we set the geometrical parameters to $R_o = 130$ nm, $R_i = 65$ nm and $H = 495$ nm in order to get a TEM transmission peak at the operating wavelength $\lambda = 1550$ nm (see Fig. 4a). Note that the peak position is independent of the incidence angle. Only its amplitude is affected by this value [19]. In addition, we demonstrate that EOT can be obtained for wavelengths greater than the peak position of the TE_{11} mode. Consequently, light propagation and transmission through a very long (transmission line) nanocoaxial waveguide is prohibited because of the absorption associated with the TEM mode. The imaginary part of the wavevector associated with the TEM mode is too large to reckon on light propagation over distance greater than $30 \mu\text{m}$

Fig. 3. Zero-order transmission spectra of two AAA made in perfect conductor (a) and in silver (b) as a function of the metal film thickness. The geometrical parameters of the structure are: $R_o = 130$ nm, $R_i = 65$ nm and $p = 65$ nm. In both cases, the incident plane wave illuminates the structure at $\theta = 45^\circ$ and it is TM polarized (magnetic field parallel to the metallic film).

Fig. 4. Zero-order transmission spectra for various AAA configurations where outer and inner radii are fixed to $R_o = 130$ nm and $R_i = 65$ nm, respectively. (a) Conventional structure illuminated at 45° corresponding to the dashed blue line of Fig. 3b (metal thickness of $H = 495$ nm). (b) Tilted AAA of 25° with respect to the vertical direction. The thickness of the metallic film ($H = 430$ nm) was chosen to correspond to a TEM peak transmission at $\lambda = 1550$ nm. (c) Classical AAA structure with inner metallic parts that stretch out from the metallic film over a distance $h = 80$ nm. This allows increasing of the impedance matching between the in- and out-coming plane waves with the TEM guided mode inside the apertures. The metal thickness is also adjusted to $H = 418$ nm in order to get a TEM peak at $\lambda = 1550$ nm. (d) Combination of the two last configurations demonstrating efficient TEM-mode excitation under normal incidence.

in the visible and the near infrared domains [22]. This can be partially bypassed by replacing the inter-conductor material, which is vacuum, by a high dielectric constant one. Consequently, the TEM peak transmission efficiency can be enhanced considering a thinner metallic film allowing the same optical path inside the apertures.

Unfortunately, the original idea of using coaxial nano-waveguides as transmission lines seems to be hardly applied [23] using conventional AAA [24] not only because of the absorption occurring during the propagation but also because of the small overlap between the incident wave and the TEM guided mode. In fact, independently of the incident homogeneous beam, the coupling remains weak because every nanoguide locally “sees” a plane wave due to its dimension compared with the illuminating wavelength. Therefore novel solutions must be found to get around this difficulty.

Fig. 5. Transmission spectra through the AAA structure presented on the top. The outer and inner radii are fixed to $\lambda = 130$ nm and $R_i = 65$ nm, respectively. As in Fig. 4c and d, the length of the conductor core part ($H + 2h$) is larger than the metal film thickness (H). The dashed red curve corresponds to the case where only the inner part of the apertures is filled with a dielectric material ($n = 2.2$) as presented on the above schema while the whole structure is surrounded by this dielectric for the blue solid curve. Normalized electric field amplitude distribution in the plane (x, z) passing through the aperture axis at $\lambda = 1550$ nm is presented on the right. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In the same paper [23], the authors suggested the use of specific nano-antennas that allow enhancement of the radiation coupling. Here we propose to study some configurations consisting on original ways for the excitation of the TEM mode without respecting either the angle of incidence or the polarization. The first proposed configuration was suggested by the group of J.J. Greffet at Ecole Centrale Paris [25]. It consists on the excitation of the TEM mode at normal incidence by tilting the axis of the annular apertures (see inset of Fig. 4b). Such structure is equivalent to conventional AAA illuminated at oblique incidence and does not bring substantial improvement to the enhancement of the coupling with the TEM mode. Nevertheless, it can be useful for photovoltaic applications where it is possible to sacrifice certain directions of illumination and certain polarizations. A typical transmission spectrum is presented in Fig. 4b where geometrical parameters were adapted to get the TEM transmission at $\lambda = 1550$ nm.

Another well-known solution that is currently used in the radio-frequency domain to increase the impedance adaptation between a coaxial antenna and the vacuum consists in stretching out the central metallic part of the nanocoax with respect to the outside electrode. This configuration was implicitly used in Ref. [23] to achieve 90% light transmission thanks to the excitation of the TEM mode. This kind of structure modification is readily achievable at radio frequencies. This is more difficult in the visible range but remains possible through manufacturing process having a nanometric resolution (Focused Ion Beam, Reactive Ion Etching, ...). Nonetheless, as in the case of conventional AAA, the TEM mode is not excited neither at normal incidence nor in TE polarization. The main advantage of this solution is to increase the coupling both at the entrance and the exit sides and to allow decreasing the metal film thickness for a fixed wavelength value (see Fig. 4c).

According to these last results, one can propose a hybrid configuration such as the one presented in Fig. 5 combining all the possible schemes and corresponding to a “realistic” model of the AAA structure considered in the studies of Kempa team [26]. From all geometrical parameters of the nanotube array, only the period and the radii are fixed as in Fig. 4. However, the axis-symmetry of the aperture is broken by shifting (both in the x and y directions) the center of the circular section of the nano-waveguide with respect

to the vertical axis. In addition, the inner part is stretched out differently from the two sides of the metallic film and the inter-conductor space and/or the (substrate + superstrate) are filled by a dielectric material ($\epsilon = 4.84$). The obtained transmission spectrum shows a complex structure composed of both TE_{11} and TEM peaks so in which one gets non-zero transmission for almost every wavelength between 500 and 2000 nm. The complex structure of the calculated spectra cannot simply connect the transmission value for a given wavelength to the geometric parameters of the structure. Roughly, one can insure that the minima appearing in these spectra, looking like absorption peaks on a continuum (see for instance peaks α and β in Fig. 5), are directly linked to the presence of a strong coupling between the TE_{11} mode and the various TEM peaks as it is shown in Fig. 3.

This result points out the reason of the light transmission experimentally observed in Refs. [17,26] even if the transmitted efficiency is weak. We can say that a coaxial structure with some defects (protuberances breaking the axial symmetry of one coaxial aperture) at the entrance and the exit sides seems more appropriate for transmission through the TEM mode than the perfect conventional structure. In this case, the fabrication defects are beneficial and could lead to more efficient structures.

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