Spatiotemporal sub-wavelength near-field light localization

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Abstract: The control and localization of light at sub-wavelength scale are theoretically demonstrated with a very simple sub-wavelength dimension structure. This is demonstrated through a peculiar structure that can support localized modes which are not linked to any plasmon resonance. It is based on the acronym “FEMTO” that is designed using 26 sub-wavelength rectangular apertures engraved into perfectly conducting metal screen. A polarization-sensitive guided mode through these nano-apertures is at the origin of the light localization. Consequently, sub-wavelength light spots can be achieved with very simple structures illuminated by temporally shaped plane waves. Three parameters are temporally controlled for this purpose: the polarization, the wavelength and the amplitude of the incident beam. It is also demonstrated that replacing the perfect conductor by a real metal with dispersion leads to accentuate both the light confinement and its localization. These results open the path to the conception of optical nano-structures dedicated to sub-wavelength light addressing.

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References and links
1. M. I. Stockman, S. V. Faleev, and D. J. Bergman, “Femtosecond energy concentration in nanosystems: coherent control,” Physica B 338, 361 (2003).
2. M. I. Stockman, D. J. Bergman, C. Anceau, S. Brasselet, and J. Zyss, “Enhanced second-harmonic generation by metal surfaces with nanoscale roughness: Nanoscale dephasing, depolarization, and correlations,” Phys. Rev. Lett. 92, 57402 (2004).
3. T. Brixner, F. J. G. de Abajo, and J. S. W. Pfeiffer, “Nanoscopic ultrafast space-time-resolved spectroscopy,” Phys. Rev. Lett. 95, 093901 (2005).
4. T.-W. Lee and S. K. Gray, “Controlled spatiotemporal excitation of metal nanoparticles with picosecond optical pulses,” Phys. Rev. B 71, 35423 (2005).
5. A. Kubo, K. Onda, H. Petek, Z. Sun, Y. S. Jung, and H. K. Kim, “Femtosecond imaging of surface plasmon dynamics in a nanostructured silver film,” Nano Lett. 5, 1123 (2005).
6. M. Aeschlimann, M. Bauer, D. Bayer, T. Brixner, F. J. G. de Abajo, W. Pfeiffer, M. Rohmer, C. Spindler, and F. Steeb, “Adaptive subwavelength control of nano-optical fields,” Nature 446, 301 (2007).
7. S. Choi, D. Park, C. Lienau, M.-S. Jeong, C. Byeon, D. Ko, and D. S. Kim, “Femtosecond phase control of spatial localization of the optical near-field in a metal nanoslit array,” Opt. Eng. 16, 12075 (2008).
8. M. I. Stockman, S. V. Faleev, and D. J. Bergman, “Coherent control of femtosecond energy localization in nanosystems,” Phys. Rev. Lett. 88, 067402 (2002).
9. X. Li and M. I. Stockman, “Highly efficient spatiotemporal coherent control in nanoplasmonics on a nanometer-femtosecond scale by time reversal,” Phys. Rev. B 77, 195109 (2008).
10. G. Lévêque and O. J. F. Martin, “Narrow-band multiresonant plasmon nanostructure for the coherent control of light: An optical analog of the xylophone,” Phys. Rev. Lett. 100, 117402 (2008).
In the last decade, several theoretical [1–4] and experimental works [5–7] were done to demonstrate the possibility of obtaining controlled local light confinement. Most of them were based on a beam-shaping technique that allows a spatiotemporal localization of light in the near field of structures composed of sub-wavelength features. Linear [8] or nonlinear, [6] such as a second harmonic generation, processes were studied. A learning algorithm is generally used through a closed-loop technique in order to design the waveform of the incident beam [6]. This loop links the diffracted pattern to the incident beam in order to optimize the time evolution of the light distribution and to get very localized light spots. More recently, Stockman et al. used the time reversal principle to get highly efficient coherent control through the excitation of local plasmon resonances of nanometric metallic structures [9].

In 2008, Lévéque and Martin theoretically proposed and studied an optical analog of the xylophone [10]. Their beautiful idea was based on the excitation of the plasmon resonance of increasing-lateral dimension metallic rectangular patches. In order to keep the resonance properties of each individual patch, it was necessary to deposit the whole structure on a gold metallic layer. Nevertheless, the obtained structure exhibits well one localized resonance per metallic patch. So, by temporally driving the wavelength (through chirped pulses for example), the authors demonstrated light localization that propagates from one to another patch according to the instantaneous value of the incident pulse wavelength. Consequently, the light confinement was obtained by only varying the wavelength value.

In this paper, we propose another design of sub-wavelength structures that can be temporally addressed in order to get localized light spots. A very simple structure that can be considered as a pedagogical example demonstrating sub-\(\lambda\) light localization is studied. In our case, the confinement is driven with both the polarization state and the wavelength of the incident beam. The idea is born thanks to the recent works on the enhanced transmission [11] that occurs when light passes through perforated thick metallic films. In fact, it was demonstrated that apertures made into such films can support guided modes or plasmonic resonances responsible on this enhancement [12, 13]. The excited fundamental guided mode has, generally, a cutoff wavelength that depends on the geometry of the aperture [14–17] while the wavelength associated with the plasmonic modes almost depends on the structure period [18]. Consequently, enhanced transmission can be obtained around the cutoff wavelength of a guided mode for periodic or aperiodic structure while it is necessary to consider a spatially periodic structure for the surface plasmon resonance.
In order to consider a structure exhibiting a polarization dependence together with a light confinement, perfectly circular aperture shapes are prohibited (even if the arrangement of holes can break the cylindrical symmetry). So, rectangular apertures are considered. As it is well-known, the fundamental mode that has no-zero overlap with incident plane wave is the TE$_{10}$ having a cutoff wavelength of:

$$\lambda_{c}^{TE_{10}} = 2a$$  \hspace{1cm} (1)

When such a rectangular aperture is engraved into finite thick metallic film and illuminated by a plane wave under normal incidence, only the fundamental (TE$_{10}$) guided mode is efficiently excited. Enhanced transmission is then obtained for wavelength values around $\lambda_{c}^{TE_{10}}$ [13] [see Fig. 1(b)]. Simultaneously, the near-field light distribution presents a spatially localized spot light [see Fig. 1(c)] due to the presence of a guided mode inside the aperture. Note here that, for thin metallic films ($h < 100$ nm), the transmission peak position is slightly red-shifted from the position of the TE$_{10}$ mode cutoff [see dotted line in Fig. 1(d)]. This property can also be used to accentuate the sub-wavelength character of the structure by decreasing the thickness as long as this latter is larger than the metal skin depth (in the case of a real metal with dispersion).

On the other hand, the same phenomenon of red-shift (see Fig. 1) is also obtained when replacing the perfect conductor by a real metal with dispersion [13].

We choose to study a structure corresponding to a specific word that can be written using some different rectangular apertures. The final goal is to achieve a spatiotemporal addressing of each letter composing this word in order to successively switch on (by transmission) each letter. In other words, the time evolution of the near-field light distribution must present instantaneous localized spots corresponding to the transmission through only one letter starting from the left and propagating to the right. Obviously, to be convincing, this effect must be obtained when the whole structure is simultaneously illuminated by an infinite plane wave.

For this purpose, and benefiting from the properties of the TE$_{10}$ guided mode, i.e. the geometrical parameters of the rectangular apertures, it is possible to write the five letters of the word “FEMTO” with a combination of different apertures. Figure 2 presents one possible way to do this with only six different small sticks (the stick is here the xy section of the rectangular aperture) where the metal is supposed to be perfectly conductor with 120 nm thickness. Note that, in Fig. 2, the width of all the sticks is fixed to 30 nm while only their length is varied from 180 nm to 324 nm in order to get light confinement in the visible range.

It is clear that the choice of the stick lengths is intuitive if we attempt to get localized light that propagates uniformly from left to right. In this case, it is necessary to consider a negative chirped plane wave (the instantaneous frequency decreases linearly with time) in order to excite successively the guided modes of the apertures toward the same direction (left to right). This is why, both horizontal and vertical stick lengths increase from the letter F to O.

This structure is then injected into a full 3D FDTD homemade code in order to determine the spectral and polarization dependence of the transmitted signal from each aperture. Hence, the 26 near-field spectra are calculated for the two polarization states in the case of a plane wave illuminating the metallic film at normal incidence. These spectra are presented on Figs. 2(b) and 2(c) for detectors [red and blue disks of Fig. 2(a)] placed at 30 nm from the output side of the metallic film. As expected [see for example the two spectra of the M horizontal sticks on Fig. 2(c)], the responses of two similar apertures are quite different because of the coupling with the closest neighbors. Nevertheless, the structure presents five well defined guided modes for each polarization without almost no significant overlap. This property is at the origin of the coherent control of the transmission through the structure.

According to spectra of Fig. 2 that give the wavelengths of the guided modes inside each
Fig. 1. (a) Schematic of a single rectangular aperture engraved into a free-standing 50 nm thick metallic film. (b) presents the two near-field spectra for the two polarization states along x (blue) and y (red) in the case of silver film. (c) is the light distribution at 30 nm from the exit side of the silver film corresponding to the transmission peak of Fig. 1(b). Spectra for perfect conductor film are presented on (d) to point out first, the well-known blue shift of the transmission peak in comparison with the case of silver film [in comparison with Fig. 1(b)] and second, the same, but smaller, blue shift that occurs when the metal thickness increases [see solid and dotted lines in (d)]. All the presented results are obtained through FDTD simulations where the silver dispersion is described by a Drude model that is given in Ref. [13].

Aperture, we consider an incident plane wave where the electric field is expressed by:

\[ E_x(t) = A_x(t) \cos(\phi_x(t) - k_z z) \]
\[ E_y(t) = A_y(t) \cos(\phi_y(t) - k_z z) \]
\[ E_z(t) = 0 \]  

(2)

where \( \phi_x(t) \) and \( \phi_y(t) \) are the instantaneous phases associated with the x and y components of the incident electric field respectively. As it is well-known, the associated instantaneous wavelengths are given by:

\[ \lambda_{x,y} = \frac{2\pi c}{\dot{\phi}_{x,y}(t)} \]  

(3)

where \( \dot{\phi}_{x,y}(t) \) is the time derivative of \( \phi_{x,y}(t) \). Because of the linear variation of the length sticks leading to a linear variation of the guided mode wavelengths, \( \lambda_{x,y}(t) \) should vary linearly with time. According to spectra of Fig. 2(b) and 2(c), we fixed their values to:

\[ \lambda_x(t) = 2.7211 \times 10^6 t_{1,3} + 3.3277 \times 10^{-7} \text{m} \]
\[ \lambda_y(t) = 2.8390 \times 10^6 t_{1,3} + 4.0628 \times 10^{-7} \text{m} \]  

(4)
These values were fixed in order to have a time delay of 30 fs between the switching of two consecutive letters.

By injecting Eq. (4) into Eq. (3) we get:

\[
\phi_x(t) = \frac{2\pi \ln(\lambda_x(t))}{7.211 \times 10^6}
\]

\[
\phi_y(t) = \frac{2\pi \ln(\lambda_y(t))}{2.839 \times 10^6}
\]

On the other hand, the temporal envelopes \( A_{x,y}(t) \) are complex functions that have to be defined so that we get equivalent light intensity for all the sticks composing the same letter. This condition is necessary to get "readable" letters. The information needed to define \( A_{x,y}(t) \) is not given on Fig. 2 because only normalized spectra are presented. Nevertheless, it is obvious that the temporal envelopes \( A_{x,y}(t) \) do not have a unique expression because the above mentioned condition can be fulfilled with an infinite number of solutions. Nonetheless, a specific and very restricting one consists to get almost the same value of the light intensity for all the five letters.

To be fulfilled, this condition imposes a set of weighting factors \( (w_{x,y}) \) for both the x and y amplitudes of the incident electric field. This factors are given in Table 1.

Consequently, \( A_{x,y}(t) \) are then defined as piecewise functions composed of six half-period sinusoidal variations presenting their maxima at times \( t_n \) given in Table 1. Their mathematical
Table 1. Wavelength and weighting factor values for specific times corresponding to the
switching of each letter. $n = 0$ and $n = 7$ correspond to the beginning and the end of the
pulse respectively. The switching of the five letters of the word “FEMTO” occurs from
$n = 1$ (for “F”) to $n = 6$ (for “O”).

| $n$ | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| $t_n$ (fs) | 0   | 30  | 60  | 90  | 120 | 150 | 180 |
| $\lambda_n^x$ (nm) | 332.77 | 417.18 | 497.40 | 567.30 | 664.90 | 741.60 | 822.57 |
| $w_n^x(10^{-2})$ | 0   | 3.818 | 2.589 | 1.488 | 2.187 | 1.182 | 0   |
| $\lambda_n^y$ (nm) | 406.28 | 496.10 | 570.30 | 663.00 | 745.00 | 834.60 | 917.30 |
| $w_n^y(10^{-2})$ | 0   | 2.121 | 1.385 | 3.852 | 3.083 | 1.305 | 0   |

expressions are given by:

$$A_{x,y}(t) = \begin{cases} 
0 & \text{for } t_0 < t < t_n \\
(w_n^{x+1} - w_n^x) \sin \omega_0 (t - t_n) + w_n^{x,y} & \text{for } t_n < t < t_{n+1} \text{ and } n = 1, 6 \\
0 & \text{for } t \geq t_7 
\end{cases}$$

(6)

where $\omega_0$ is equal to $5.2360 \times 10^{13}$ rad/s. By injecting Eqs. (5) and (6) into Eq. (2) one obtains
the result presented on Fig. 3.

By illuminating the whole structure with this time- and polarization-shaped plane wave the
near-field light distribution in transmission presents consecutive confinement and localization
in front of rectangular apertures composing only one letter. Figure 4 shows snapshots that cor-
respond to the excitation of guided modes of only apertures composing one letter. These latter
are extracted from the movie of Fig. 5 (Media 1).

We note that the addressing of each letter is almost obtained even if small parts of light are
guided through adjacent sticks [see the horizontal bottom stick of the letter O in Fig. 4(d)].

In summary, by temporally shaping the incident plane wave together with a polarization
control, it is possible to obtain localized (sub-λ) light spots through a very simple structure
consisting on rectangular apertures perforated into a metallic screen. The excitation of a guided
mode at its cutoff frequency is at the origin of the transmitted light that leads to this control.
It is clear that this result opens the way to the design of a lot of geometries based on the
extraordinary transmission phenomena for the coherent control of light. The annular aperture
arrays [19] are promising structures in the sense that they allow light transmission for very small
inter-conductor space [17]. In this case, the polarization control can be obtained by breaking
Fig. 4. Light intensity distributions at 30 nm above the exit metallic interface at times corresponding to the switch on of each letter. Note that the time origin corresponds to plane wave injection at the entrance side of the structure. So, $32.98 - 30 \approx 3 \, fs$ are necessary for light to go through the four apertures composing the letter "F".
Fig. 5. (Media 1) Movie showing the spatiotemporal light distribution at 30 nm from the output side of the structure (down). The amplitude of the two electric field components are given at the top of the movie through the instantaneous position of the two red and blue circles. For example, the instantaneous amplitude of the electric field is about 0.04 at time \( t = 92.16 \) fs corresponding to the switching of the letter "M" \((E_x = 0.016\) and \(E_y = 0.038\)). The obtained intensity 30 nm in front of the eight apertures is then \( I = 1 \) meaning that a confinement factor of 590 is obtained. This latter greatly depends on the geometry of the aperture.

the cylindrical symmetry of the apertures as demonstrated in Ref. [20]. Such structures can be considered as a viable alternative to the near-field optical microscopy to locally address the illumination on a geometrically well-known sample. The information encryption can also be envisaged through such a system where the \( \lambda \)-polaro shaped beam consists on the information that can only be read if associated with the sub-wavelength structure playing the role of the key.

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