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Resonant evanescent complex fields on dielectric multilayers

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Complex light fields including evanescent Bessel beams can be generated at dielectric interfaces by means of oil-immersion optics operating in total internal reflection conditions. Here, we report on the observation of evanescent complex fields produced on a dielectric multilayer through the interference of surface modes resonantly sustained by the multilayer itself. The coupling to surface modes is attained by modifying the wavefront of an incident laser beam in such a way that the resulting intensity distribution in k-space matches the dispersion of the surface mode. The phase of surface modes can be further controlled and two-dimensional vortex beams can be also produced, according to the same working principle.

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The increasing capability of engineering light wavefronts by combining holographic techniques with the use of resonant surface electromagnetic modes is enabling new tools in various fields such as optoelectronics, microscopy, nanofabrication or optical tweezing[1-6] In this framework, the exploitation of Surface Plasmon Polaritons (SPPs) as near field energy carriers plays a relevant role because of the high degree of confinement of the electromagnetic field provided at the metal-dielectric interface and the possibility of manipulating the SPPs by nano-structuring the metallic surface[7,8] In much simpler configurations, the direct coupling of tightly focused beams [9-11] or complex beams to SPPs through prisms or immersion optics has also been explored[12-14] An evanescent Bessel beam is indeed characterized by a ring in its angular spectrum [15] and a non-diffractive behavior over a near field distance [11], and it has been already demonstrated that the natural wavevector filtering due to the resonant coupling condition may be exploited to produce evanescent Bessel beams [9,11,16-18].

Recently published works have demonstrated that one dimensional photonic crystals (1DPC) sustaining Bloch Surface Waves (BSWs) can be used as an alternative to metallic films sustaining SPPs to some extent [19-23]. An advantage of using photonic structures relies on the high Q-factors of the BSW resonances due to the low ohmic losses, especially in the visible range [24]. As an additional advantage, the multilayer structures can be tunable in terms of working wavelength (from UV to IR) and polarization response [25, 26].

Despite SPP and BSW rely on a different physics, the phenomenological analogy of these two effects is continuously inspiring new opportunities for replacing metallic thin films with dielectric multilayers [20,27].

Here we aim at exploiting BSWs to generate bi-dimensional complex optical fields with no need for surface nanostructures. More specifically, we employ a Spatial Light Modulator (SLM) to modify the wave-front of an incident laser beam in such a way that a controlled coupling of complex BSW field can occur through an oil-immersion objective.

Fig 1 a) Schematic view of the optical setup. b) s-polarized reflectivity profile calculated at \( \lambda = 532 \) nm as a function of the normalized transverse wave-vector component of an s-polarized plane wave incident on the multilayer from the glass side. c) Sketch of the sample stage with the oil-immersion objective oil-contacted to the glass substrate of the multilayer. The green dashed lines represent the laser beam path; the continuous green lines represent the electric field distribution of the BSW mode.
The experimental setup is sketched in fig. 1a. A linearly polarized TEM$_{00}$ beam (CW frequency doubled Nd:Yag laser, wavelength $\lambda = 532$ nm and power 10 mW) is collimated by a beam expander (BE) constituted by a low Numerical Aperture (NA = 0.1) objective, a 50 $\mu$m pin-hole and a lens. The Gaussian beam coming out from the BE propagates toward the display of a phase only SLM (Holoeye PLUTO-VIS-016-C). The diameter of the beam is slightly larger than the display in order to maximize the SLM efficiency. The beam reflected by the SLM is Fourier-transformed by the lens L1 placed in the L1 focal plane can be used to filter out the zero-order. Subsequently, the laser beam can be eventually conditioned by using polarizing elements, e.g. a Quarter Wave Plate (QWP) or a Half Wave Plate (HWP). The lens L2 performs a 1:1 image formation of the BB placed onto the Back Focal Plane (BFP) of an oil-immersion objective (NA = 1.49), which is oil-contacted to the glass substrate of the 1DPC. Thanks to a beam splitter (BS), the light collected by the high NA objective can be imaged on a Charge Coupled Device (CCD) camera via a movable lens (L3). By changing the position of L3, either the BFP or the direct plane (DP) of the High NA objective can be imaged on the CCD.

The 1DPC structure is a multilayer having the following stack sequence: (Ta$_2$O$_5$-SiO$_2$) $x$ 4. The Ta$_2$O$_5$ layers are 70 nm thick ($n_h = 2.08$) while the SiO$_2$ layers are 210 nm thick ($n_g = 1.45$), with the exception of the last SiO$_2$ layer, which is only 180 nm thick. A more detailed description of the 1DPC employed here can be found in previous works [21,28]. The structure is designed to sustain TE-polarized reflectance profile as function of the normalized transverse wave-vector component $k_T/k_0 = n_g \sin(\theta_{inc})$, where $k_T$ is the transverse wave vector, i.e. the wavevector component parallel to the sample surface, and $k_0$ is the free-space wave vector of the incident radiation. $n_g = 1.5$ is the glass substrate refractive index and $\theta_{inc}$ is the angle of incidence of a plane wave impinging on the 1DPC from the glass side. The profile, calculated at $\lambda = 532$ nm, shows a reflectance dip located at $k_T/k_0 = 1.139$ with a Full Width Half Maximum (FWHM) $\approx 0.008$. The appearance of the dip is associated to the resonant coupling of the free-space radiation to the BSW mode. The SLM is used to shape the illumination beam incident on the 1DPC trough the oil-immersion objective. When the phase function of an axicon is generated on the SLM, a ring-shaped beam is projected in the BFP of the oil-immersion objective. The diameter of the ring can be adjusted by controlling the parameters of the Computer Generated Hologram (CGH) displayed on the SLM, meaning that we can adjust the transverse wave-vector components of the laser beam incident on the sample [29]. When the diameter of the ring projected in the BFP is such that the laser beam emerging from the oil-immersion objective contains a transverse wave-vector component equal to the BSW wave-vector, the light incident on the samples is partially reflected at the glass/1DPC interface and partially coupled to the BSW. The reflected light appears as a bright ring in BFP imaging, as showing in fig. 2a (the white arrow indicates the incident beam polarization). If the BSW coupling conditions are matched, the reflected light on the BFP image features a dark ring corresponding to the reflectivity dip that one would obtain in Kretschmann configuration [21]. The dark arcs are oriented accordingly to the polarization of the incident beam in such a way that BSW coupling occurs in an s-polarized condition in DP imaging. A large donut-shaped intensity distribution is collected enclosing a complex pattern suggesting the presence of converging waves toward the optical axis (fig. 2b). It is well known that surface modes can be imaged through immersion optics by collecting the corresponding leakage radiation [30]. However, the large amount of reflected light may hinder the direct image of the surface mode. In order to overcome this effect, we slightly changed the position of the oil-immersion objective, in such a way that the leakage radiation only is collected (fig. 2c).

The BFP image in fig. 2c shows two bright narrow arcs with the same orientation of the dark arcs in fig. 2a. By switching to DP imaging (fig. 2d), we observe a magnified image of the central region of fig. 2b, from which the external bright donut shaped light is excluded. Fig 2e and 2f are magnified views of portions (marked by the yellow dashed boxes) of the BFPs imaged respectively in fig. 2a and 2c. Figure 2g shows a comparison between the two vertical cross sections taken along the yellow dashed lines fig. 2e (black line) and 2f (red line). The black line profile shows a dip centered at $k_y/k_0 = 1.135 \pm 0.002$ and a FWHM = $0.011 \pm 0.004$. The peak of the red line is centered at $k_y/k_0 = 1.142 \pm 0.002$ and has a FWHM = $0.027 \pm 0.004$. The small displacement between the two peaks may be attributed to the slightly different magnification factor in the two BFP images. Additional uncertainty is due to the pixel sampling of the image. Such analysis confirms that the two BFP images are somehow complementary and that the dip observed in the reflected spot corresponds to surface propagating BSW-coupled radiation. In the following the DP imaging configuration will be considered, since it allows for directly image the surface distribution of light coupled to the BSW mode.
the BSW coupled radiation at the air/1DPC interface when the incident beam is polarized along the $y$-axis (corresponding BFP in the inset). The radiation coupled to the BSW propagates along the air/1DPC interface, converging toward the center of the field of view, where a bright spot is produced. The fringes observable in the figures are caused by interference of the BSW-coupled radiation that is radially propagating on the surface. A similar focusing effect has been reported in a previous work, wherein a circular grating was used to couple converging BSWs [31]. The bright arcs in the BFP rotate accordingly to the polarization orientation (see inset in the figure), thus confirming the polarization dependence of the coupling mechanism. The polarization selectivity of the coupling mechanism would require therefore an azimuthal polarization of the incident beam in order to generate an effective Bessel beam distribution of the evanescent fields that would be characterized by a full ring in its angular distribution.

To overcome such a limitation, a QWP is introduced along the beam path so that a circularly polarized beam is obtained. Since the coupling occurs only for the s-polarized component of the incident beam, we expect that at each instant, only half of the donut shaped spot will have the correct polarization condition to be coupled to the BSW. By integrating the acquisition over a time much larger than a single period of rotation of the electric field, the intensity homogeneous leakage radiation ring observed in the fig. 4a is obtained. Since the CGH displayed on the SLM is azimuthally invariant (see inset in fig. 4a), each point of the ring generated is in phase with all the others. If the direct plane is imaged, the surface distribution of the BSW-coupled radiation confirms that at the center of the image a bright spot is generated, caused by constructive interference of all the converging BSWs (fig. 4b).

As a further check of BSW coupling we can observe the fluorescent trace of the laser BSW by covering the surface of the 1DPC with a homogenous fluorescent layer, in such a way that the fluorescent molecules act as near-field probes for the excitation field [10,21,24]. The image in fig 3b confirms that the laser light is propagating along the surface and focusing in a diffraction limited spot. Unfortunately, the fluorescence image has an intrinsic limited resolution that does not allow a detailed analysis of the focal spot. Part of the fluorescence excited on the surface of the 1DPC couples in turn to the BSW and it is therefore delocalized on the surface [21,22,31]. An analysis of the intensity profile taken across the dashed yellow line in fig. 3a shows that the spot in the center has a FWHM = 158 ± 54 nm, while the periodicity of the fringes is estimated to be $P_{\text{fringes}} = 241 ± 54$ nm, which is consistent with the theoretically predicted value of

$$\frac{\lambda}{2 \times k_f/k_0} = 233 \text{ nm}$$

Here, the uncertainty of the estimation is mainly given by the discretization of the image introduced by limited pixel size of the CCD camera. It has to be pointed out here that both the periodicity of the fringes and the beamwidth of the focal spot are fixed for a given multilayer design since both of them depend on the spatial frequency of the BSW.

When the incident beam is linearly polarized, the polarization-selective coupling of BSW limits the focusing effect along one direction. In order to provide a detailed analysis of the focal spot, part of the fluorescence image has an intrinsic limited resolution that does not allow for changing anything in the optical setup or re-alignment.

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References (abbreviated form)