Beaming Light from a Subwavelength Aperture
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Light usually diffracts in all directions when it emerges from a subwavelength aperture, which puts a lower limit on the size of features that can be used in photonics. This limitation can be overcome by creating a periodic texture on the exit side of a single aperture in a metal film. The transmitted light emerges from the aperture as a beam with a small angular divergence (approximately ±3°) whose directionality can be controlled. This finding is especially surprising, considering that the radiating region is mainly confined to an area with lateral dimensions comparable to the wavelength of the light. The device occupies no more than one cubic micrometer and, when combined with enhanced transmission, suggests that a wide range of photonic applications is possible.

Light transmission through an individual aperture, such as a hole in an opaque screen, has been studied for centuries. According to standard diffraction theory, apertures much smaller than the wavelength of light transmit very poorly and diffract light in all directions uniformly. These two properties, transmission and diffraction, are considered fundamental constraints in manipulating light on a very small scale for technological purposes. Ideally, one would like to be able to not only get more light through such structures but also to channel it in a well-defined direction as a collimated beam. Here we demonstrate an approach to satisfy both requirements.

The excitation of surface waves, or surface plasmons, on metallic surfaces gives us a path to achieving this goal. Surface plasmons (SPs) are collective electronic excitations, or charge density waves, which are characterized by intense electromagnetic fields confined to the surface (1–4). For instance, SPs can boost the transmission of light through subwavelength hole arrays in metal films (5–7), a phenomenon which has been analyzed theoretically by various groups (8–15).

One way to couple free propagating light to surface plasmons, on metallic surfaces give us a path to achieving this goal. Surface plasmons (SPs) are collective electronic excitations, or charge density waves, which are characterized by intense electromagnetic fields confined to the surface (1–4). For instance, SPs can boost the transmission of light through subwavelength hole arrays in metal films (5–7), a phenomenon which has been analyzed theoretically by various groups (8–15).

We then patterned an identical bull’s eye on both sides of a suspended Ag film (groove periodicity, 500 nm; groove depth, 60 nm; hole diameter, 250 nm; film thickness, 300 nm). By recording the transmission spectra at various collection angles for the bull’s eye on both sides of a suspended Ag film (groove periodicity, 500 nm; groove depth, 60 nm; hole diameter, 300 nm; film thickness, 300 nm), the tail above 800 nm is an artifact of the spectral measurement. The structure is illuminated at normal incidence with unpolarized collimated light. The spectra were measured using a Nikon TE200 microscope coupled to an Acton monochromator and a Princeton Instruments CCD (charge-coupled device) camera. (C) Optical image of the sample of (A) illuminated from the back at its wavelength of peak transmission (λmax = 660 nm) using a 50-nm band-pass filter. (D) Angular transmission-intensity distribution derived from the spectra of (B) at λmax (Inset) Schematic diagram of the structure and the beam divergence and directionality of the transmitted light at λmax in the far field.
emerges in the shape of a well-defined beam with an observed full-width at half-maximum (FWHM) divergence of ±5°. When the finite angular resolution of our apparatus is taken into account, the actual beam divergence is deduced to be ~±3°. This low divergence is all the more surprising, considering the small size of the apparent spot at the exit surface. Figure 1C shows an optical image of the exit surface of a bull’s eye structure at its peak transmission wavelength, recorded at the same scale as the FIB image (Fig. 1A). Light emission is mainly confined to a central area around the hole with lateral dimensions not exceeding 1 µm or two periods of the structure.

To elucidate the physics of the beam formation on the exit side, we prepared and analyzed other structures. In particular, we studied a more basic structure with one dimensional symmetry consisting of a single slit surrounded by a linear groove array on both side of the film (Fig. 2A). The slit is 40 nm wide, 4400 nm long, and the corrugation has a 500-nm period.

By varying the output collection angle (Fig. 2B), we determined that the transmission spectrum is, again, angle-dependent. The maximum transmission intensity drops and the peak splits into two peaks that move to lower and higher wavelengths, respectively, implying that at a given wavelength the light emerges with maximum intensity at a particular angle from the surface. For example at λ = 580 and 800 nm, the corresponding values are 0° and 30° from the normal, respectively. As in the case of the bull’s eye structure of Fig. 1, the measured FWHM divergence of these lobes is ±5° (Fig. 2D), which corresponds to an actual divergence of ±3° when corrected for our angular resolution. In the absence of corrugation on the output surface, the narrow slit diffracts the transmitted light isotropically.

To verify the equivalence of the in- and out-coupling mechanism between light and the metallic corrugated surface, we compared the output-coupling mechanism between light and the surface plasmons. The FWHM are all order of magnitude wavelength matches quite well the input dispersion relation governing the respective propagation processes. The beam output angle as a function of wavelength matches quite well the input dispersion relation for such a grating (inset, Fig. 2B). This strongly indicates that SP modes are involved in a similar manner on both the input and output sides. In other words, the activated surface modes reradiate back into propagating light, following the energy and momentum conservation dictated by the corrugated surface.

Once again the emission spot size, as measured with an optical microscope, is centered on the subwavelength aperture and is mainly confined to an area with lateral dimensions on the order of two periods (compare Fig. 2, A and C). To further demonstrate the confined spatial extent of the reradiating area, we recorded high-resolution images for numerous samples using an optical microscope and a near-field scanning optical microscope (NSOM). These images were then profiled (inset, Fig. 3) for a bull’s eye structure at its wavelength of maximum transmission. The NSOM data was recorded at 1.5 µm above the structure with an uncoated tip in order to avoid evanescent coupling with the surface plasmons. The FWHM are all ~1 µm and, thus, are comparable to the optical wavelength.

The combination of low divergence angle and small emission area for the transmitted light is, at first glance, rather surprising. If we were to treat our structures as simple apertures, a standard far-field diffraction (19) calculation for λ = 580 nm (for instance, the peak wavelength in Fig. 2B) would require an aperture width of 4900 nm to achieve the observed divergence of ±3° FWHM, a width far larger than that of the
actual openings in our experiments. This implies that the exit surface surrounding the aperture must also be involved in the reradiation process, as we already inferred from the existence of the dispersion relation. Nonetheless, we do not have uniform emission from an area as large as implied by the above estimate. If the structure surrounding the central aperture emitted light very weakly, could this contribute to explain the small observed angular divergence? Within the resolution limit of our apparatus, we cannot preclude the presence of some emission from the surface whose intensity diminishes rapidly as a function of lateral distance from the aperture. Given our optically thick film, the source of this emission can only come from scattering of the light emerging from the aperture. To test this possibility, we implemented a simple first-principle model based on interference in the far-field of light scattered at the center of each groove with a laterally variable emission intensity given by a curve fit to the experimental results (Fig. 3, inset). In our model, the phase of the emission at each groove is proportional to the distance travelled by the surface wave from its origin at the aperture. These SPs travel slightly slower than light in free space due to retardation by the metal and, as a consequence, emission normal to the surface occurs at a wavelength slightly larger than the period. With this model, we are able to reproduce the overall features of the observed angular divergence of Figs. 1D and 2D, as well as the dependence of directionality on wavelength (Fig. 3).

Perhaps the most non-intuitive aspect of this phenomenon is the fact that scattering at the grooves of only a small fraction of the light emerging from the aperture can create such a narrow beam by interference (20). Even though the emission remains heavily confined to the immediate vicinity of the sub-wavelength aperture, the secondary contribution from the surface plasmons launched and scattered on the exit surface narrows the divergence dramatically from that of a normal isotropic distribution. The coupling of the electromagnetic wave of the SP back to light follows the dispersion curve impeded by the metal and, as a consequence, emission normal to the surface occurs at a wavelength slightly larger than the period. With this model, we are able to reproduce the overall features of the observed angular divergence of Figs. 1D and 2D, as well as the dependence of directionality on wavelength (Fig. 3).

The vibrational dynamics of the retinal chromophore all-trans–to–13-cis photoisomerization in bacteriorhodopsin has been studied with mid-infrared absorption spectroscopy at high time resolution (about 200 femtoseconds). After photoexcitation of light-adapted bacteriorhodopsin, the transient infrared absorption was probed in a broad spectral region, including vibrations with dominant C=C, C=N, and C=NH stretching mode amplitude. All photoproduction modes, especially those around 1190 reciprocal-centimeters that are indicative for a 13-cis configuration of the chromophore, rise with a time constant of ~0.5 picosecond. The results presented give direct vibrational-spectroscopic evidence for the isomerization taking place within 0.5 picosecond, as has been suggested by previous optical femtosecond time-resolved experiments but questioned recently by picosecond time-resolved vibrational spectroscopy experiments.