Coherent control of the absorption and scattering of an isolated plasmonic nanoantenna integrated in a silicon waveguide

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ABSTRACT

In this paper, we use an on-chip approach to experimentally demonstrate that the absorption and scattering of a subwavelength plasmonic nanoantenna can be manipulated by using coherent illumination. To do so, we integrate the nanoantenna in a gap separating two silicon photonic waveguides so that it can be illuminated from its both sides by two coherent beams with controlled amplitude and phase. We show experimentally that scattering can be modulated by about one order of magnitude, whilst higher values could be obtained by further optimization. This finding paves the way towards coherent all-optical data processing in subwavelength devices integrated on silicon-compatible chips.

Keywords: silicon photonics; coherent perfect absorption; nanoantennas; hybrid photonic circuits.

1. INTRODUCTION

Interference between counter-propagating monochromatic waves incident upon an absorbing medium can result in either enhanced or suppressed absorption and scattering, ultimately enabling the regime known as coherent perfect absorption [1]-[2]. This provides a very suitable way towards all-optical processing without nonlinearities, which therefore may be performed at low levels of optical power and ultra-high speed [3]. Although most demonstrations of this phenomenon have made use of thin absorbing layers formed by arrays of plasmonic nanoantennas operated under normal free-space excitation, the principles of coherent manipulation of absorption and scattering are also applicable to individual nanoantennas, which could result in all-optical processing in subwavelength scales. However, coherent illumination of individual nanoantennas from free-space is highly challenging, which has prevented the demonstration of the coherent manipulation of single subwavelength entities. Here, we demonstrate experimentally the coherent control of an isolated plasmonic nanoantenna with foot-print much smaller than the wavelength. In particular, we show how the scattering and absorption of the nanoantenna, whose response is dominated by a dipolar electric resonance, are deeply modulated when the phase difference between the feeding counter-propagating signals is changed.

2. DESCRIPTION OF THE STRUCTURE

Figure 1(a) sketches the nanophotonic structure we address in this work: a strip nanoantenna is built on a subwavelength gap separating two silicon waveguides [4], which provide the guided paths for counter-directional illumination with controlled phase. We consider that the nanoantenna (centred at z=0) is perfectly aligned with the waveguide axis to maximize optical interaction. Such interaction will mainly consist of scattered radiation (part of which will be guided and directed towards the output ports, *s*, and the rest will be scattered out of the system, *s*') and absorption (*a*). The extinction of the system will therefore consist of two terms: *s*' and *a*. If the input fields have the same amplitude and the phase difference between them is $\Delta\phi = 0$ at z=0 (Fig. 1(b)) there will be constructive interference at the position of the nanoantenna (green curve in Fig. 1(e)) and both scattering (*s* and *s*') and absorption (*a*) will be maximized. Indeed, under the proper conditions, such output fields can be completely suppressed, reaching a regime of coherent perfect extinction, for which the signals at the two output ports of the system vanish. If the amplitude is the same but $\Delta\phi=\pi$ at z=0 (Fig. 1(c)), there is destructive interference at the position of the nanostructure, and the local fields are zero (blue curve in Fig. 1(e)). As a result, both absorption and scattering will be extremely minimized. Assuming a nanostructure with very small dimensions we can reach the condition of coherent perfect transmission since the guided fields do not "see" the nanostructure. Finally, if one of the inputs (B) is eliminated (Fig. 1(d)) we get single-beam illumination. In this case, the square of the electric field at the particle position is the average of the previous cases, so we will have both scattering and absorption. Backward scattering will produce guided waves towards the input port and forward scattering will interfere with part of the incoming guided field (the portion that is not absorbed or scattered) to produce a certain output signal at port B. In general, it can be seen that not only the scattering and the absorption of the nanoantenna can be modulated by controlling the phase difference, but also the transmission and reflection along the waveguides, which could be employed for on-chip coherent data processing.

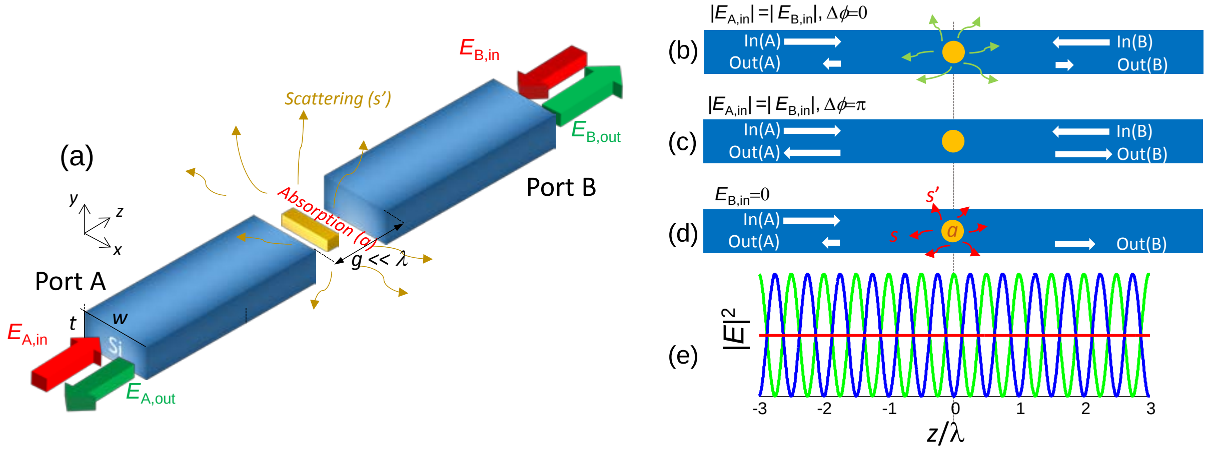

Figure 1. Coherent manipulation of a plasmonic nanoantenna. (a) In our practical implementation, the plasmonic nanoantenna is inserted in a subwavelength gap created in a dielectric (silicon) waveguide. (b)–(d) Schematic representation of a waveguide (blue) with two ports (A and B) having a metallic nanoantenna (orange circle) positioned in its optical axis and at z=0. Scattering, absorption and transmission will depend on the amplitude and phase relation between counter-propagating guided waves, leading to enhanced scattering/absorption and reduced transmission for constructive interference at z=0 (b), reduced scattering/absorption and enhanced transmission for destructive interference at z=0 (c) and standard single-beam scattering, absorption and transmission when one of the input signals (B) is switched off. (e) $|E|^2$ along the waveguide – without the nanoantenna - for the three cases: green (b), blue (c) and red curve (d).

3. EXPERIMENTAL RESULTS

We demonstrate the proposed system using a silicon photonic circuit as shown in Fig. 2. In brief, light enters the system via an integrated silicon waveguide, which is the spilt up in two paths that will feed the plasmonic nanoantenna (inset in Fig. 2) in opposite directions. The nanoantenna is designed to support an electric-dipole plasmonic resonance at telecom wavelengths [4]. There is a path length difference ΔL between both feeding waveguides so, provided that the effective index of the TE-like waveguide mode is n the phase difference between both input ports can be simply obtained as $\varphi = 2\pi n\Delta L/\lambda$. The scattered intensity will be proportional to $2\cos^2(\varphi/2)$. In particular, the fabricated chip had $\Delta L \approx 20$ µm. This way, we implement a wavelength-dependent phase shift without modifying the amplitudes of the paths. Notice that such a phase shift can also be obtained by other means, for instance, by inserting a phase-modulator – which in silicon can operate a speeds of tens of GHz - in one of the waveguides. This approach would allow to dynamically change the phase shift at a single wavelength.

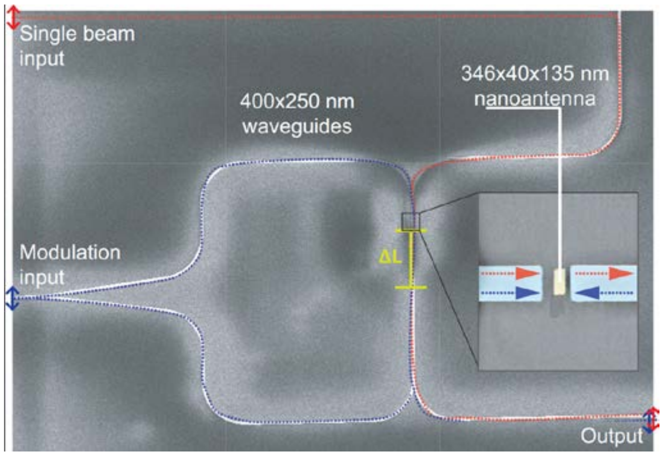

Figure 2. Scanning electron images of the silicon photonic circuit to demonstrate coherent control of isolated nanoantenna. Inset: detail of the nanoantenna inserted in the gap. Blue (red) lines indicate the paths followed by the guided light for dual-beam (single-beam) illumination). The chip was fabricated using silicon-compatible nanofabrication tools (details can be found in [4]).

The circuit was experimentally characterized at telecom wavelengths using a set-up similar to that described in [5]. Therefore, we were able to measure both on-chip transmission as well as normal scattering in a single shot. Moreover, by careful selection of the input and output ports, the chip shown in Fig. 2(a) allows for measurement of both transmission and normal scattering for one-way as well as two-way excitation of the nanoantenna. Experimental results for both transmission and scattering are shown in Figs. 3(a) and 3(b) respectively. Notice that absorption (a) is not directly measurable in our system, but it can be considered as proportional to scattering (s'), as it is the case in plasmonic nanostructures whose response is dominated by an electric dipole resonance, so its spectrum should look similar to that depicted in Fig. 3(b). In transmission (Fig. 3(a)), we see a modulation of the response for dual-beam illumination of ~3 dB in a broad bandwidth. Larger contrast could be obtained by an optimized design of the system, so all-optical coherent data processing with this approach seems feasible. The peaks observed in the single-beam transmission can be attributed to the creation of undesired recirculation paths in the circuit (see Fig. 2) but we do not observed them in our measurements in Ref. [4]. In scattering measurements (Fig. 3(b)) we observe that the dual-beam response shows an intensity modulation in comparison with the single-beam response (showing a peak at ~1.5 µm, which correspond to the nanoantenna plasmonic resonance). Such modulation, with about one order of magnitude in depth, is attributed to constructive (maxima) and destructive (minima) interference of the counter-propagating beams at the nanoantenna position. In general, the measured spectrum agrees well with the expected $2\cos^2(\varphi/2)$ response. A similar modulation should be expected for the nanoantenna absorption.

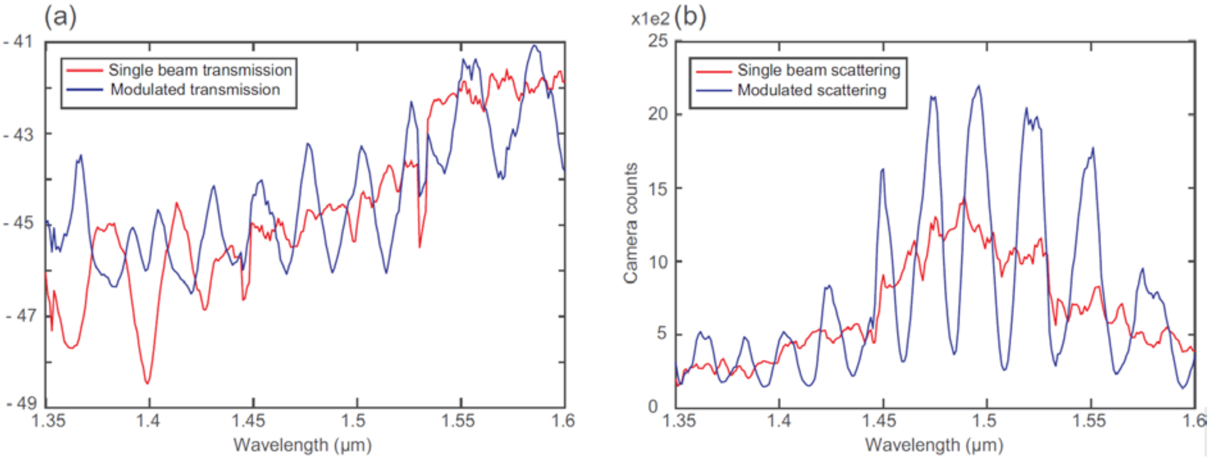

Figure 3. Experimental results. (a) Transmission and (b) normal scattering measured spectra for the single-beam (red) and dual-beam (blue) transmission paths. Waveguides are fed by using the fundamental TE mode of the silicon waveguide.

4. CONCLUSIONS

In conclusion, we have demonstrated coherent control of the scattering and absorption of a single plasmonic nanoantenna integrated in a silicon chip at telecom wavelengths. Using standard silicon circuitry, we are able to illuminate the nanoantenna using counter-propagation light beams whose phase is wavelength-dependent as a consequence of the waveguide dispersion. We show that the scattering – and, as a result, also the absorption - of the nanoantenna can be either enhanced or suppressed depending on the phase shift between counter-directional beams. Moreover, port-to-port transmission is also modulated depending on the phase shift. A modulation contrast of about one order of magnitude (~10 dB) in scattering and ~3 dB in transmission is observed over a 15 nm bandwidth, as a result of the broad resonance of the employed nanoantenna. Being our system suitable for dense integration of multiple nanoantennas on a chip, this approach could lead to massive ultrafast coherent all-optical signal processing in silicon.

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