Subwavelength focusing at optical frequencies achieved by an inverse designed photonic silicon integrated device

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Perfect lensing has been extensively studied since 2000, when Pendry [1] described how evanescent modes allow restoration of subwavelength detail at the image plane.
The structures for perfect lensing can be based on dielectric-based photonic crystals (PCs) [2] whose dispersion properties can be engineered so that at specific frequencies in the vicinity of the photonic band gap, negative refraction [3, 4] and subwavelength imaging [5] can be achieved. The first experimental evidence was obtained in the microwave regime and demonstrated single-beam negative refraction and superlensing in the valence band of a two-dimensional PC [6]. Subwavelength focusing experiments operating at optical frequencies have been done with photonic lenses made of air holes in a semiconductor slab. The measurements have been done by different techniques [7, 8], with the most accurate and detailed being the SNOM measurements [9, 10].

In this work, we have attempted an innovative approach in the field of subwavelength focusing through photonic crystals. We have designed a photonic crystal silicon integrated lens, able to focus an impinging front wave in a spot freely located by us, by an inverse design method based on a genetic algorithm and the bidimensional multiple scattering theory [11]. These techniques allow us to obtain unexpected structures with the desired functionality [12], in contrast to the inefficient direct design based in intuition and the “trial and error” scheme. The device consists of a matrix of holes of 300 nm diameter in a semiconductor slab where some voids have been selectively removed by the genetic algorithm (see Fig.1.a). As the calculation volume limits the design to a bidimensional space, the obtained 2D optimized PC structure has been simulated by a 3D finite difference time domain method to validate the design, with positive results (Fig.1.b-c).

The experimental demonstration has been achieved by the fabrication of the device in silicon and measurements of the field intensity distribution on the device surface by Scanning Near-field Optical Microscopy (SNOM).
The device has been fabricated by electron beam lithography and fluorinated ICP plasma etching in a 340 nm thick silicon layer on top of a silicon dioxide box-layer (Silicon-On-Insulator technology).
The experimental near-field measurements show the performance of the device (Fig.2.a-b), and the correlation with the theoretical results and simulations (compare Fig.1.c and Fig.2.b).
The device has shown subwavelength focusing in the vicinity of the silicon surface, with the measured full width at half maximum of the focus being $0.23\lambda_0$, which is in good agreement with the finite difference time domain method simulations (Fig.2.c), and which overcomes the diffraction limit in air, where the measurements are made.
Moreover, the lens has shown additional advantages over previous photonic devices. The design method allows us to position the focus in a location freely determined by us, which contrasts with the lenses based in the equifrequency curves, where the focus must be placed in the symmetry axis and near the photonic structure.
The inverse design also allows non-punctual sources to be dealt with, in our case with a plane wave front. Finally, the fabricated lens presents a performance over a broad bandwidth, experimentally demonstrated between 1500 and 1580 nm, while the previous PC lenses have a bandwidth of a few nanometers [10].

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Figures

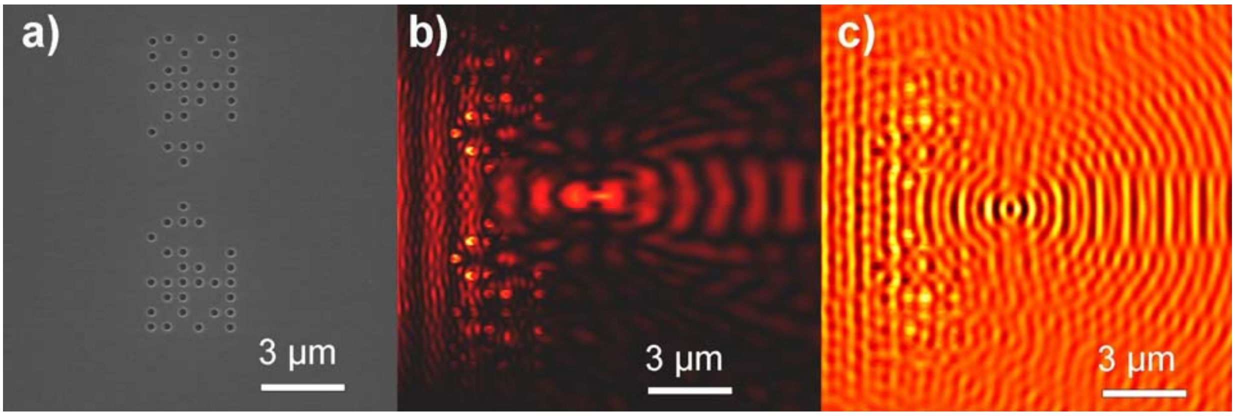

Figure 1. (a) SEM image of the fabricated photonic device. **(b)** Intensity of the electric field distribution calculated by FDTD on the surface of the designed device. **(c)** Intensity of the electric field distribution calculated by FDTD after the addition of a constant field.

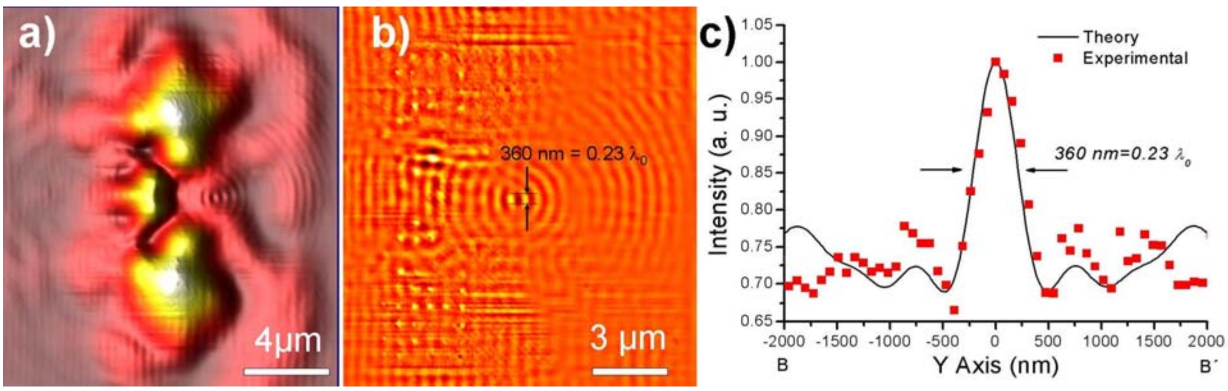

Figure 2. (a) Direct measurement of the electric field intensity by SNOM. **(b)** SNOM measurement after filtering the optical noise, showing agreement with the simulation of Fig.1.c, with transversal full width at half maximum of the focus of $0.23\lambda_0$. **(c)** Comparison of the transversal sections of the calculated and simulated electric field intensities.