Nanometer-sensitive wideband opto-mechanical switching concept

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Abstract

The present paper is concerned with the mechanically extremely sensitive reflection switching concept of a free-space wave impinging on an array of dielectric or semiconductor pillars. Splitting the pillars of a 2D periodic array in its resonant reflection regime at a prescribed wavelength into two parts with a low-index gap of a few nanometers between parts cancels the reflection of a plane wave under normal incidence. The underlying principle lies in the strong and abrupt discontinuity of the electric field component parallel to the pillar axes caused by the gap. The electromagnetic field distribution is consequently deeply perturbed and no longer corresponds to that of an optical resonance of the array; this suppresses the reflection. The electromagnetic analysis of a silicon pillar array leads to the design of a gapless experimental model fabricated by microsystem technologies that exhibits a broad reflection maximum of a few tens of nm at a prescribed wavelength in the visible and near-IR range, and of a pillar structure with nanometer-thick low-index gap exhibiting no reflection peak over this wide wavelength range. A transmission ratio of 1:30 at a 1080 nm peak wavelength between a gapless and a 1.5 index, 30 nm-thick gap structures was measured.

1. Introduction

The present contribution is in the field of opto-mechanical switching of a free-space wave with applications in displays, projectors, and diverse sensors. Its applications, technologies and componentry are therefore distinct from opto-mechanical switches where the switching function is applied to a wave confined in a waveguide in the objective of short switching time and miniaturization, for instance in data center networks. Such is, e.g., an integrated frustrated total reflection switch [1]; the wide variety of proposed integrated designs is reviewed in [2]. The optical function of the present switching principle is also distinct from switching arrays performing optical packet routing as reviewed in [3]. Planar free-space wave switching is usually performed in a pixelated form to attribute a definite value of an optical parameter to each pixel, and to locally control the duration of the ON-OFF reflection states. Since the early work of L J Hornbeck on the DMD Digital Micromirror Device [4], several modulation and switching effects have been evaluated and applied for spatial light modulators as reviewed in [5]. Recently, radically new physical switching effects have been explored - that cannot be reviewed here - such as all-optical modulation / switching in a silicon waveguide containing highly nonlinear metal nanorods in their epsilon-zero regime [6], or else, in the THz range, transmittance modulation is obtained at the charge transfer plasmon frequency by electrically tuning the conductivity of a metasurface composed of graphene islands between metallic blocks [7].

The physical effect retained in the present contribution relates with that of resonant reflection first revealed experimentally and analysed in 1985 [8] whereby a dielectric waveguide grating exhibits total reflection of an incident free-space wave in case the phase-matching (or synchronism) condition is satisfied. This condition expresses the spatial frequency equality between the propagation constant \( \beta = 2\pi n_e / \lambda \) of a waveguide mode of effective index \( n_e \) and the sum of the grating k-vector \( K_g = 2\pi / \Lambda \) and the in-plane projection of the incident wave k-vector \( 2\pi \sin \theta / \Lambda \); \( \lambda \) is the wavelength in vacuum, \( \Lambda \) the grating period, and \( \theta \) the incidence angle. The
synchronism condition finally writes \( \lambda = \frac{\Lambda}{n_\text{e} + \sin \theta} \) if the incidence medium is air, and \( \lambda/\Lambda = n_\text{e} \) under normal incidence. Any physical effect that modulates the grating period \( \Lambda \) or the waveguide mode effective index \( n_\text{e} \) can cancel the reflection occurring at a prescribed wavelength \( \lambda \). For instance, exerting an in-plane mechanical force on an elastic substrate supporting the waveguide causes a variation of the period \( \Lambda \) of the array [9]; the same effect can be caused electrically with an elastomer substrate [10]. Fluidic actuation by immersing the grating corrugation and repelling the liquid electrically [11] modifies the propagation constant \( \beta \) of the excited mode; the same effect can be obtained by electrically tuning a liquid crystal [12]. The waveguide grating doesn’t have to be a light-guiding layer or channel with shallow periodic corrugation; it can simply be a periodic array of deep subwavelength 1D trenches or 2D pillars as established in the early work of S M Rytov [13]. These can be considered as a uniform layer with an equivalent refractive index. If the equivalent index is larger than the refractive index of the surrounding media, the layer can be considered as a uniform slab waveguide that propagates waveguide modes along the plane of the array [14] susceptible of exhibiting resonant reflection peaks. Worth noticing here is the characteristic of these waveguide grating resonances to be rather narrow spectrally.

However, the above analogy between a 1D or 2D deeply segmented layer and a uniform layer of equivalent refractive index does not account for all resonant effects that the actual subwavelength periodic structure does exhibit: there is another set of modes, named grating modes, excited by an incident free-space wave. These grating modes are electromagnetic field configurations satisfying the boundary conditions at the wall of the trenches or pillars. They propagate up and down and interfere constructively or destructively in the incidence and transmission half-spaces according to the relative phase difference they have accumulated. How the modal fields are excited, propagate, reflect, and interfere is described in detail in the vivid example of a polarization transformer using a sliced 1D grating [15]. It is here worth noticing that this grating mode interference phenomenon leads to reflection maxima that can be rather broad spectrally unlike grating-coupled waveguided mode resonances [16]. The phase of such grating mode at a given wavelength depends on the period \( \Lambda \) of the array, the duty cycle in one period, the refractive index of the grating material, and, most importantly here, on the geometry. Thus, for a 2D grating, such as a pillar array, introducing a low-index interlayer within the pillars will drastically change the boundary conditions and thus also change the interference conditions set to provide maximum reflection.

The next section will describe the underlying electromagnetic phenomenology of this nanometer-sensitive switching concept between ON and OFF reflection states. Then its experimental demonstration will bring the confirmation of the effect of a low index interlayer gap on the nanometer-sensitive reflectance modulation.

### 2. Results

#### 2.1. The optomechanical switching concept and underlying electromagnetic phenomenology

The structure considered here comprises a fused silica substrate that supports a hexagonal array of cylindrical silicon pillars of diameter \( d \), height \( h \), period \( \Lambda \), as illustrated in figures 1(a) and (d). Figure 1(b) shows the reflection spectrum of the array in the visible wavelength range under normal incidence giving rise to a reflection peak in the blue range for an exemplary design with the complex refractive index of silicon. To find out the nature of this relatively broad maximum at 450 nm wavelength we have launched a general calculation of the normalized 0th order reflected power at constant wavelength over a wide parameter domain for the period \( \Lambda \) of the array and the height \( h \) of lossless silicon pillars on a silica substrate by using a modal method [17]. The result is represented in form of the 2D chart of \( h \) versus \( \Lambda \) at wavelength \( \lambda = 450 \) nm (figure 2). This chart exhibits three zones of very different aspect joined at 450 nm and 310 nm period: at the right-hand side of the 450 nm limit there are propagating diffraction orders in both incidence medium (usually air) and in the SiO\(_2\) substrate; the 0th order reflection coefficient is everywhere smaller than 1. In the 310 nm \( < \Lambda < 450 \) nm region there are propagating diffraction orders in the substrate of refractive index 1.45; here too, except at \( \Lambda \) close to 370 nm, high reflection coefficients are absent. The \( \Lambda < 310 \) nm domain is the ‘subwavelength’ parameter range where the 0th order reflection coefficient exhibits an orderly pattern of 100% conditions. In the subwavelength range the power reflection peaks at 100% among two types of lines: there are continuous thin lines exhibiting thickness constrictions oriented monotonously from the bottom-right to the top-left of the chart; these bear the character of waveguide modes whose effective index is given by the ratio \( \lambda/\Lambda \) since the effective index increases with the structure height and, as shown in the inset in figure 2, their transverse electric field exhibits a number of maxima corresponding to their mode order plus 1, i.e. in the present case a TE\(_1\) mode. There is a second category of lines along which the reflection peaks at 100%: they are meandering lines of large width; these do not correspond to waveguide modes, but rather to constructive interferograms of grating modes as established in [16] in the very similar case of 1D binary walls and grooves. They also exhibit line constrictions with the same general orientation as the thin lines. How these two sets of lines cross or repel was elucidated in [18]. As the imaginary
Figure 1. Nanogap reflection suppression. (a) and (d) Representation of a 5 nm air gap in a hexagonal array of silicon pillars under normal incidence on a SiO\textsubscript{2} substrate. Geometry: pillar height \( h = 77 \) nm, diameter \( d = 98 \) nm, array period \( \Lambda = 194 \) nm. (b) and (c) Reflection spectra of (a), (d) geometries. (c) and (f) Normalized electric field modulus \( (E_z) \) over a pillar cross-section (plane containing \( x \) and \( z \) axes, located at \( y/\Lambda = 0.5 \)) at \( \lambda = 450 \) nm. (g), (h) and (i) 2D chart of normalized reflected power versus pillar height and period at constant wavelength (450 nm) and period/diameter ratio (194/98) with (g) no gap and lossless silicon \( (n = 3.917 + 0i) \), (h) no gap and lossy silicon \( (n = 3.917 + 0.012i) \) and (i) 5 nm gap and lossy silicon. (j) 2D scan of reflected power versus pillar height \( h \) and wavelength \( \lambda \) at constant period (\( \Lambda = 194 \) nm) and diameter \( (d = 98 \) nm) considering \( \lambda \)-dependent dispersion lossy silicon and zero gap. The white cross identifies the blue working point of figure (b).

Figure 2. Parametric scan of pillar height \( h \) versus period \( \Lambda \) of a lossless hexagonal array with fused silica substrate showing the normalized 0th order reflected power at constant wavelength (450 nm) and normal incidence in three diffraction regimes, from right to left: propagating diffraction orders in incidence air medium and silica substrate, in silica substrate only, and subwavelength regime. The subwavelength area exhibits two types of 100% reflection locus: thick meandering lines and thin monotonous lines of negative slope, the latter corresponding to waveguide modes as illustrated for a first order mode by the two-lobe cross-sectional (xz) transverse electric field inset.
part of the pillars’ permittivity is set to zero in figure 2, it can be considered that this chart gives the general property of any hexagonal array made of below-band-gap semiconductor pillars of refractive index between ca. 3 and 4 versus dimensionless period \( \Lambda/\lambda \) and height \( h/\lambda \) normalized to the wavelength by simply multiplying the scale of coordinate axes by \( 1/450 \) nm \(^{-1} \). Introducing a minute vertical discontinuity of a 5 nm air gap (figure 1(e)) results in a dramatic reduction of the reflection peak. Figures 1(c) and (f) show in false colors the mapping of the electric field component \( E_z(y, z) \) parallel to the pillar axes at the wavelength 450 nm of the reflection peak. \( E_z(y, z) \) plays a key role in the wideband switching principle: this field component belongs to the constructive interferogram of grating modes giving rise to 100% reflection. As shown in figure 1(f), the air gap imposes a very strong discontinuity on the \( E_z \) field; this also deeply modifies the other field components and destroys the reflective constructive interference. A general physical insight can be gained by representing the reflection spectra of figures 1(b) and (e) in a zoomed restricted area of the \( (\Lambda, h) \) chart of figure 2. Figure 1(g) corresponds to gapless pillars made of lossless silicon at the peak wavelength \( \lambda = 450 \) nm of figure 1(b); the white cross in this chart locates the conditions of maximum reflection, i.e., \( \Lambda = 194 \) nm and \( h = 77 \) nm. This figure reveals that the broad blue reflection peak of figure 1(b) is located on the meander of minimum height of figure 2. Figure 1(h) is the same except that the silicon pillar is now lossy with its complex refractive index in the visible range. Interestingly, the narrow lines and the nodes of the meandering lines have disappeared because of their resonant character in an absorptive material. Besides, the only meandering line still exhibiting a high reflection coefficient is the bottom one. Still with lossy silicon, figure 1(i) shows vividly the effect of a 5 nm air gap: the whole spectrum is shifted to notably larger height, leaving the working point of figure 1(b) in a wide zone of quasi-zero reflection. The 2D chart shown in figure 1(j) explores the relationship between wavelength dependent reflection and the height \( h \) of the nanopillars at fixed period \( \Lambda = 194 \) nm (corresponding to the same working point of figure 1(b)), and with lossy silicon; it meaningfully shows the wideband character of the reflection peak, and the wide blue zone at the right-hand side of the white cross expresses that the OFF state extends all over the visible range.

Although the visible range is very interesting for applicable devices and systems such as displays, proximity sensors, and acoustic sensors, the experimental and technological demonstration has been made in the near infrared where silicon is quasi-lossless for sake of interpretation simplicity.

2.2. Experimental wideband suppression of resonant reflection
A straightforward experimental confirmation of the electromagnetic principle enabling the wideband suppression of resonant reflection of a silicon pillar array was devised: it permits to bypass the technical actuation problem of electromechanically controlling the spacing between two arrays at nanometer resolution. Two types of pillar arrays were fabricated: a reference array with monolayered amorphous silicon (aSi) pillars of height \( h \), and a second one with multi-layered pillars consisting of a silicon section of height \( h/2 \), a thin silicon dioxide layer of 30 nm thickness, and another silicon section of height \( h/2 \). SiO\(_2\) was chosen as a readily available material with low refractive index (\( n = 1.45 \)) to mimic a low index gap. The functional element was designed to have its operational point at \( \lambda = 1080 \) nm. The samples were measured in transmission. This does not affect the conclusions that can be drawn for the reflective states as the device shows by design very little absorption (less than 2% @ 1080 nm). Figures 3(a) and (b) show SEM images of the respective samples. The hydrogen silsesquioxane (HSQ) e-beam resist layer was kept on top of the pillars as it does not noticeably affect the optical result due to its low refractive index (\( n \approx 1.4 \)). Using a tunable Chameleon OPL laser source and a gallium arsenide detector (see figure 4) the transmission spectrum of the reflective and low-reflection states was measured. As can be seen in figure 5(a)), there is a much higher transmission exhibited by the sample with the sandwiched SiO\(_2\) nanolayer than by the monolayer aSi pillars. Furthermore, both structures show to be polarization independent. Finally, this experimental result of figure 5(a) gets carried over into the lossless (\( \Lambda, h \))
Figure 4. Experimental transmission measurement setup using a tunable laser with GaAs light intensity detector; (1) tunable laser source (800 nm - 1500 nm), (2) Linear polarizer, (3) lens system to focus light onto sample ($f = 20$ cm), (4) gallium arsenide detector.

Figure 5. Experimental result and simulation of the effect of a 30 nm SiO$_2$ interlayer on transmission and reflection (a) Measured TE and TM transmission spectra under normal incidence of two float glass-based pillar arrays of 260 nm pillar diameter, 640 nm period composed of 300 nm aSi (black curves), and of 150 nm aSi, 30 nm SiO$_2$ gap, 150 nm aSi (red curves). (b) Lossless simulation of the reflection coefficient in a 2D ($\Lambda, h$) chart at constant wavelength 1080 nm in the subwavelength period domain. (c) Same with a 30 nm SiO$_2$ gap at the middle of the aSi pillars. The white cross locates the 100% reflection point of the gapless structure.

2D chart of the gapless structure (figure 5(b))) and the structure with gap (figure 5(c))) at the constant wavelength 1080 nm of the reflection maximum. The subwavelength domain of both 2D charts is limited at 720 nm period since at $\Lambda > 720$ nm first order diffraction orders have a propagating character in the float glass substrate of 1.5 refractive index. The location of the corresponding white cross, on the first meandering line like in figure 1(g), essentially confirms the interpretation derived by the phenomenological model.
3. Conclusions and prospects

The creation of a nanometer-scale air-gap that vertically bisects pillars was confirmed to suppress the resonant reflection peak of a pillar array. Electromagnetic analysis and simulations reveal that there are two distinct electromagnetic phenomena leading to 100% reflection peaks in periodic arrays made of a dissipationless pillar material. One relies upon the excitation of a waveguide mode of the equivalent waveguide that the periodic subwavelength array of pillars represents; the reflection peaks in such case are very narrow. The other reflection phenomenon relies upon the constructive interference of reflecting grating modes; the reflection peaks in this case are spectrally broader which is well adapted to display and projector applications where RGB pixels of some tens of nanometer spectral width are used. The introduction of an air gap somewhere at the middle of the silicon pillars provokes a huge discontinuity on the electric field component along the pillar axes which in turn deeply perturbs the other electromagnetic field components. The simulated finding was experimentally verified in the

![Figure 6](image_url)

Figure 6. Schematics of process-flow; left column: simple aSi pillars (no interlayer), right column: pillars with 30 nm SiO2 interlayer. Pre-process, (a) sputtering, (b) oxygen plasma (c) resist spin coating, (d) e-beam lithography, (e) resist development, (f) deep reactive ion etching.
NIR using two passive structures: one without gap, a second one with a low index interlayer: for the gap to have a definite thickness, a solid-state nano layer of silicon dioxide was used. The pillar array fabrication was carried out by means of microsystem technologies, and the tunable laser transmission measurements demonstrated the existence of polarization independent high and low transmissive states according to expectations since the pillar distribution is hexagonal. To demonstrate a dynamic prototype, the specific major challenge of stiction has to be addressed. It is still an open issue at the present stage. A perspective worth exploring could be the association of the electrical actuation mechanism with an electric field compensating for the Van der Waals force [19].

4. Materials and methods

4.1. Fabrication process flow

First (figure 6(a)), amorphous silicon (aSi) as well as silicon dioxide (SiO2) were DC magnetron sputtered onto a float glass wafer. For the ON-state, a single layer of aSi was deposited whereas for the OFF-state a consecutive three layer aSi-SiO2-aSi deposition was carried out. All thicknesses were measured by ellipsometry as well as on SEM cross-sections. An oxygen plasma cleaning (figure 6(b)) of the surface was carried out before spin coating the e-beam resist (figure 6(c)) to dehydrate the surface and to wash away any impurities. HSQ XR1541 006 from Dow Corning was used as a negative e-beam resist. The resist was spin-coated (figure 6(c)) at low rotational speed of 2000 rpm, corresponding to approx. 170 nm thickness of HSQ. The e-beam exposure (figure 6(d)) was carried out using a 50 nA beam, and a dose of 3000 C cm−2. SEM inspections of patterns at the center and at the corner revealed only a difference of 2 nm in pillar diameter, thus no proximity effect correction was needed. The array size was 250 μm × 250 μm. The e-beam patterned resist was developed (figure 6(e)) in tetramethylammonium hydroxide (TMAH) for 2 min. The final process step - the etching of the pillars - (figure 6(f)) was carried out using deep reactive ion etching (DRIE).

4.2. Measurement setup

A tuneable Chameleon OPO laser source and a gallium arsenide detector were used to measure the transmission spectrum of the reflective and low-reflection state. For each wavelength the transmitted power of the sample was measured and normalized to the transmitted power through the fused silica substrate.

4.3. Simulation software

The optical reflection spectrum simulations were carried out using a code written at Fraunhofer IISB and cross-checked using a commercially available RCWA code [17]. The near-field cross-section plots were produced by the same commercial RCWA code.

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Data availability statement

No new data were created or analysed in this study.

Disclosures

The authors declare no conflicts of interest.

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