FDTD study of quasi-random photonic structures obtained by electrochemical etching

Josep Ferré-Borrull[1], Mohammad Mahbubur Rahman[1], Ivan Maksymov[2], Lluís F. Marsal[1], and Josep Pallarès[1]

(1) Departament d'Enginyeria Electrònica, Elèctrica i Automàtica
Universitat Rovira i Virgili Avda. Països Catalans 26, 43007 Tarragona, Spain
(2) Kharkov National University of Radio Electronics, 14 Lenina Ave., 61166, Kharkov, Ukraine

lluis.marsal@urv.cat

1. Introduction

Photonic crystals are structures with very relevant properties that come up from the periodic structuring at the wavelength scale[1, 2]. In this sense, they are not crystals in the sense of molecular crystals, but metacrystals with photonic properties beyond those of their constituent materials. On this basis, many new materials have been studied and applied in photonics, for instance metamaterials achieve negative refractive index with the proper periodic combination of the metallic and dielectric components[3]. There exist however, non-periodic structures with remarkable photonic properties based on their geometrical characteristics: quasicrytals may show complete photonic band gaps with lower refractive index contrast than their periodic counterparts because of their higher rotational symmetry[4], random photonic structures take advantage of Anderson localization to achieve random lasers[5].

In this communication we report on the investigation on a different kind of structures: random structures obtained by electrochemical etching. More concisely, we study macroporous silicon and nanoporous anodic alumina structures. Photonic crystals based on macroporous silicon are usually obtained by electrochemical etching after a previous lithography to define the periodic pattern. If this first step is omitted, the macropores grow randomly on Si but with a certain degree of order, giving rise to properties in-between those of the periodic and of the random structures. Nanoporous anodic alumina[6,7] is a material widely investigated and applied in nanotechnology[8]. It is obtained by the electrochemical etching of aluminium and, under the adequate conditions, the porous structure shows a self-ordered lattice with a two-dimensional triangular periodic arrangement[6,7]. The lattice constant can be tuned from some tens of nanometres up to some hundreds. Although this triangular arrangement can be achieved over a long range if a prepatterning on the aluminium surface is applied[9], in the absence of such preprocessing the regular triangular arrangement is broken into domains with a size of some tens of lattice sites and randomly oriented. Fig. 1 shows an example of each of the structures. Fig. 1a) corresponds to the surface of a random macroporous silicon sample, while Figs. 1b) and 1c) correspond to a nanoporous alumina structure.

A certain degree of order can be appreciated in the figures, for both structures. In this work we will study the photonic properties of such structures by means of FDTD calculations, and in particular, the existence of photonic pseudo-gaps and Anderson localization.

2. Results and discussion

As an example of the results obtained so far, Fig. 2 shows the result of the calculation of transmittance on a selected substructure of the nanoporous anodic alumina structure. The calculations have been performed by choosing a substructure of the structure in Fig. 1b) with a definite size and computing with the help of FDTD the transmission of a plane wave with a Gaussian frequency spectrum through the substructure. The chosen substructure is previously idealized by locating the positions of the pores by means of standard image processing techniques and by replacing such pores by ideal circular holes. The transmission spectrum through the structures is then normalized to the spectrum of the propagation in free-space of the same Gaussian beam. The spectra in Fig. 2 correspond to the average of 20 spectra corresponding to 20 substructures at different sites on the sample. The plots correspond to increasing sizes of the subset, as indicated in the caption. The graphs show also the standard deviation of the transmittance for the set of substructures.

These spectra show that, with increasing size of the sample subset, a minimum in the transmission, that can be denominated as a pseudo-gap, appears around the normalized frequency $\omega a/2\pi c=0.42$. Table 1 summarizes the pseudo-gap parameters for the different substructure sizes. This pseudo-gap appears in the frequency range corresponding to a characteristic distance of the same order of the average interpore distance in the sample. The widening of the low transmittance region indicates that, as the thickness of the structure increases, the photonic band gap effect becomes more intense.

3.- References

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Figures and tables

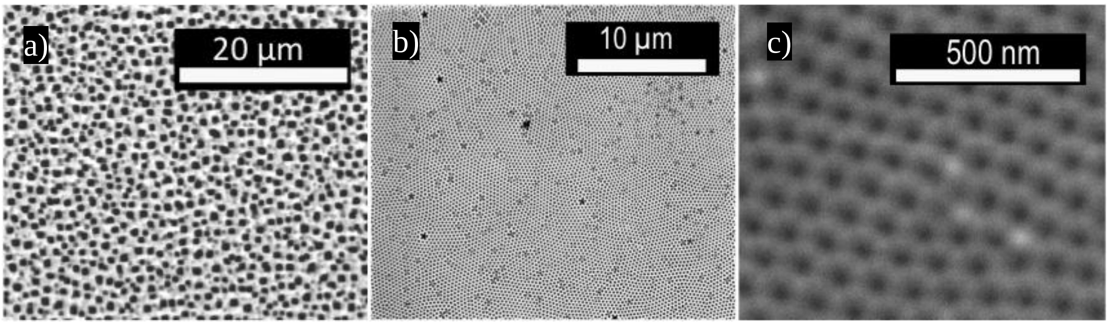

Figure 1. a) SEM micrograph of the surface of a random macroporous Si sample, b) SEM micrograph of a nanoporous anodic alumina sample where the local ordering and the breaking into domains can be appreciated, and c) magnified view of the nanoporous anodic alumina where the triangular arrangement of the pores and some dislocation points are illustrated.

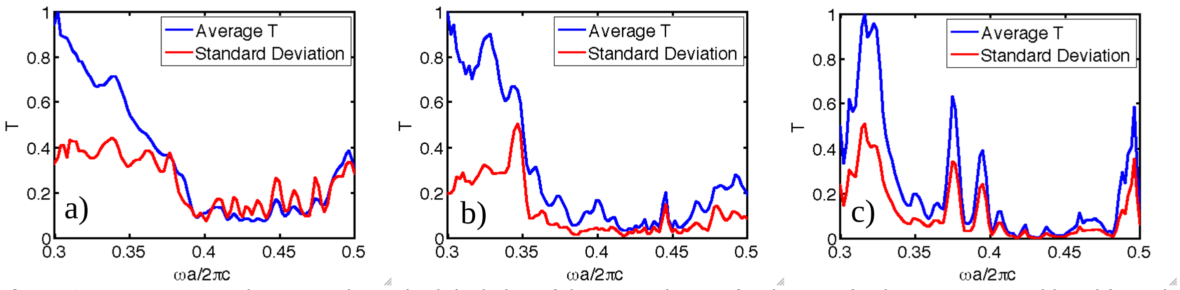

Figure 2. Average transmittance and standard deviation of the transmittance for the set of substructures considered for a defined substructure size. a) 5.1 µm × 5.1 µm, b) 6.3 µm × 6.3 µm and c) 7.6 µm × 7.6 µm.

Substructure Size (µm×µm)	Pseudo-gap lower limit (ωa/2πc)	Pseudo-gap upper limit (ωa/2πc)	Pseudo-gap width (ωa/2πc)
5.1 × 5.1	0.41	0.44	0.03
6.3 × 6.3	0.40	0.44	0.04
7.6 × 7.6	0.41	0.46	0.05

Table 1. Pseudo-gap limits and pseudo-gap width for the different subset sizes for the TE polarization. The pseudo-gap is estimated by the largest continuous range with transmittance below 0.1.