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LIFSHITZ LOCALIZATION-BASED RECONFIGURABLE PHOTONIC CRYSTALS

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ABSTRACT: *We theoretically investigate programming the functionality of photonic crystals (PCs) by reconfiguring the random location of defects. It is shown, via numerical finite-difference time-domain simulations, that the random spatial location of defects, implemented as identical changes in refractive index with respect to the host lattice, has the potential to enable realizing a large number of functions, from optical switching, based on the transition from localized to extended light wave propagation states, to beam steering, and slow light functions. The reconfigurability concept exploits nanofluidic capillarity in nanochannels to change the refractive index properties of individually addressable fluidic-based defects.* © 2011 Wiley Periodicals, Inc. Microwave Opt Technol Lett 53:2721–2724, 2011; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26441

Key words: *photonic crystals; reconfigurability; nanofluidics; random defects; lifshitz localization*

1. INTRODUCTION

The transmission of photonic crystals (PCs) [1, 2] may be tailored in analogy to that of electron transmission in semiconductors [3]. In particular, dielectric PCs' transmission exhibits photonic band gaps [1, 2], in analogy to the energy band gaps of semiconductors [3]. On the other hand, disrupting the PC's periodicity, by introducing widely-separated defects, may give rise to the appearance of, ideally, a single-wavelength (zero-width) pass band within the band gap, at which a localized light (cavity) mode can exist [1, 2, 4, 5]; this in analogy to the discrete energy level introduced in a semiconductor band gap when it is lightly-doped [3]. Furthermore, when the number of defects introduced in the PC is such that modes in adjacent defects (''impurities'') overlap, then light propagation by hopping from defect to defect becomes possible [6–10]. In particular, this is manifested in the appearance of a relatively narrow pass band within the band gap, through which light propagation is now allowed [6–10]; this is in analogy to impurity-band conduction (IBC) in a highly-doped semiconductor at low temperatures, where, due to the reduced inter-impurity separation, the electronic wave functions at neighboring impurity atoms increasingly overlap and electron propagation by hopping from atom to atom becomes possible [3].

The motivation for exploiting analogies between PCs and semiconductors is rooted in the possibility of discovering new ways to enhance the properties of (or even enabling new) photonic devices. Instances of these research efforts are typified by the following. The creation of localized modes [1, 4] in semiconductor PCs to confine light in small volumes for the purpose of enhancing the host material's optical emission properties [5]. The creation of coupled cavities [7, 8] to enable light propagation by hopping, permitting wave guiding along arbitrarily-shaped paths [9], as well as highly-efficient nonlinear optical frequency conversion and perfect transmission through sharp bends [7, 11].

In this letter, we present an approach to programming the functionality of PCs by reconfiguring the location and concentration of arrays of defects.

2. LIFSHTIZ LOCALIZATION-BASED DOPING OF PHOTONIC CRYSTALS: A STUDY

We exploit an analogy to the concept of Lifshitz localization (LL) of electron states in semiconductors [3]. In LL, as opposed to the, perhaps, more familiar Anderson localization [3], impurity state potential wells of equal energy depths are introduced at random locations within the periodic lattice; these states are localized if the concentration of impurities, N, is low, so that $\alpha N^{-1/3}.\gg 1$, where α^{-1} is the single-well state radius, and delocalized if the concentration of impurities, is high, so that $\alpha N^{-1/3}.\sim 1$ [3].

To make PC functions programmable, one varies the defect density and location, so that the light propagation properties are tailored to be either localized or delocalized.

The proposed concept was investigated strictly via numerical finite-difference time-domain simulations, using the commercially available software *Lumerical*®, from Lumerical Solutions. A magnetic dipole source, launching a TE-mode wave, was selected as the excitation with wavelength between 1 and 2 μm. PML boundary conditions delimited the simulation volume, which was strictly limited to the PC, i.e., no waveguide transitions were included. The PC host geometrical features are similar to those employed by Foresi et al. [4] in a one-dimensional fabricated structure.

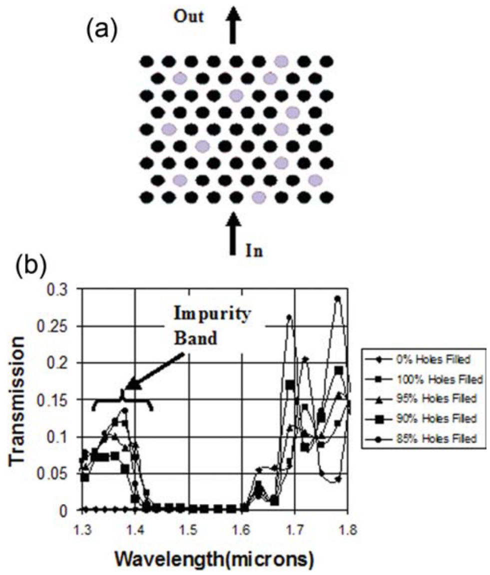

Figure 1 (a) Top view sketch of 9-layer triangular lattice PC on SOI substrate with a 0.2-μm-thick single-crystal Si layer (white background, $n = 3.48$) on a 1.0 μm SiO_2 ($n = 1.45$) layer, with 0.55 μm-deep, 0.13-μm radii air holes (gray, $n = 1$), and 0.42-μm lattice constant. It has 85% LD implemented by defining defects with refractive index $n = 1.8$. (b) Transmission characteristics for various percentages of disorder. Black circles are filled holes, gray circles are empty holes. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

To implement the Lifshitz disorder (LD) model [3], the refractive index of randomly-chosen holes is set different from unity. In practice, this change in refractive index would be effected by filling the holes with a fluid of the appropriate refractive index, see below. For a given percentage of defects (i.e., ''filled'' holes), the hole positions are generated by a uniform random number generator. We studied the effect of disturbing the PC periodicity with various degrees of LD. The calculated results are shown in Figure 1. It can be seen how, as the percentage of holes filled (refractive index $n = 1.8$) is increased, a pass band (impurity band) within the band gap, around 1.35 μm, builds up. These results suggest that only certain sets of holes need to be filled, and still result in creating a pass band. These defects could be chosen to be far apart to facilitate accommodating the nanochannels required to fill/purge the holes during a reconfiguration, see below. The rise in pass band transmission with percentage of liquid-filled holes would embody the function of a light switch, which either blocks (for 0% of holes filled), or allows (for higher percentages of holes filled) light propagation around 1.35 μm. As the percentage of holes filled increases, propagation around 1.35 μm changes from forbidden to delocalized. Evidently, the random location of defects creates shallow donor-type states, which open a transmission band within the band gap [1, 3].

One of the aims of the proposed device concept is to have the capability of effecting light beam steering by way of dynamically reconfiguring arrays of defects. This was simulated within a 19-layer PC, as shown in Figure 2. A light pulse was launched from the input **In**, and the transmitted amplitudes after propagating straight to output **Out_S**, and around a 90° bend to output **Out_L** were computed, for the set of ''liquid-filled'' hole defects shown as black circles, in Figure 2(a). Clearly, the reconfiguration of the PC to form the bend of ''liquid-filled'' defects forms a region of delocalized wave propagation, causing the light to turn around the bend. The residual amplitude of the light propagating straight through, to that making the 90° turn, is about 10%, Figure 2(b).

As is well known [3], the electron mobility due to hopping transport is very low. Therefore, one would expect that the random location of widely separated defects would give rise to light slowing/delay. This is demonstrated in the following simulations. The delay of a signal propagating through a 19-layer PC, under various conditions of defect population disorder, was determined. In particular, computed were the delay in a PC with all holes filled (155fs), and the delay in a PC populated with a random pattern of liquid-filled holes (272fs), Figure 3.

The delay was computed by capturing the peaks of the input and output pulses, and taking the difference between the times at which they occurred [12]. These results indicate that the random defects, causing hopping transport, produce the largest light slowing. The idea behind the defect pattern shown is to, first, introduce the signal into a delocalized-transport region in the PC, with minimum reflection, and then create a region where transport is via hopping, thus, at a slower speed [13].

3. NANOFLUIDICS CONSIDERATIONS

In an actual device, it is envisioned that the dynamic reconfiguration of the defects will be effected by exploiting nanofluidic capillarity in nanochannels (i.e., hole defects), so that the dielectric properties of individually addressable fluidic defects can be changed, thus enabling the realization of a large number of functions.

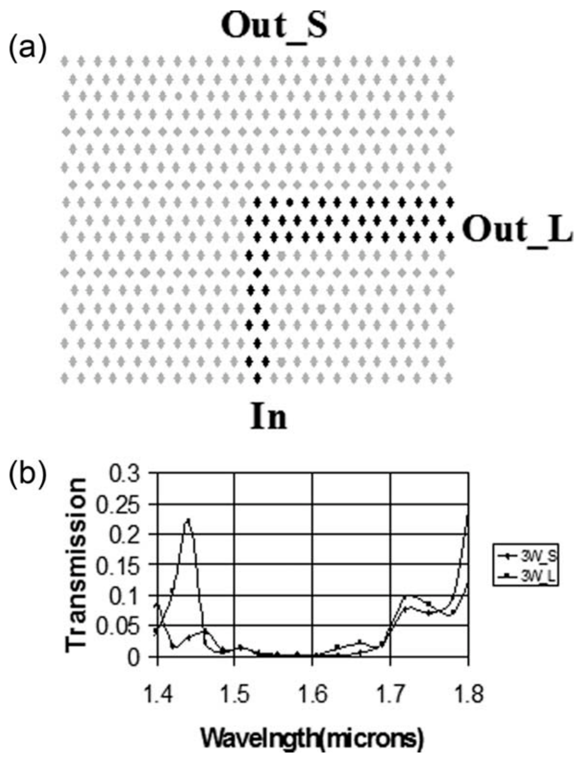

Figure 2 Top view sketch of 19-layer triangular lattice PC on SOI substrate with a 0.2-μm thick single-crystal Si layer ($n = 3.48$) on a 1.0-μm SiO_2 ($n = 1.45$) layer, with 0.55-μm deep, 0.13-μm radii holes (gray, $n = 1$), and 0.42-μm lattice constant. (a) PC host with 90° right turn bend made out of liquid-filled (black circles, $n = 1.8$) holes. (b) Transmission characteristic for straight propagation (**In**-to-**Out_S**) and propagation around the 90° bend (**In**-to-**Out_L**)

We must point out that our approach is distinctly different from the ''optofluidics'' approach of Psaltis and coworkers [14, 15] which, predicated upon soft lithography, effects tuning, i.e., shifting the wavelength response of optical devices, by controlling fluid flows with various refractive indices. In particular, the latter approach [14, 15] does not teach the advantages afforded by individually addressing/creating randomly-positioned defects, as per the Lifshitz concept hereby introduced. For these same reasons, while our approach is general enough to include them, it is also different from, and not anticipated by, those discussed by Monat et al. [15], Kurt and Citrin [16], Ebnali-Heidari et al. [17]. In addition, our approach is also a distinct, low-power consumption alternate suitable for outer space applications, compared with schemes relying on localized heating, e.g., Ref. 18.

Figure 4(a) sketches a simplified one-dimensional rendition of our concept. Because of capillary forces, the fluid is driven from the reservoir into the holes, consequently filling all of them. Then, by designing a fluidic system (not shown) to purge individual defects, one could create any desired defect pattern. The fluidics system would be placed on top of the Si PC layer and bonded to it. A simulation of the nanofluidics dynamics for filling a hole was conducted to compute the pressure drop across a cylindrical hole, using the software *FLUENT*®, Figure 4(b). The pressure drop was found to be of the order of MPas. This rules out prior-art approaches based on soft PDMS valves,

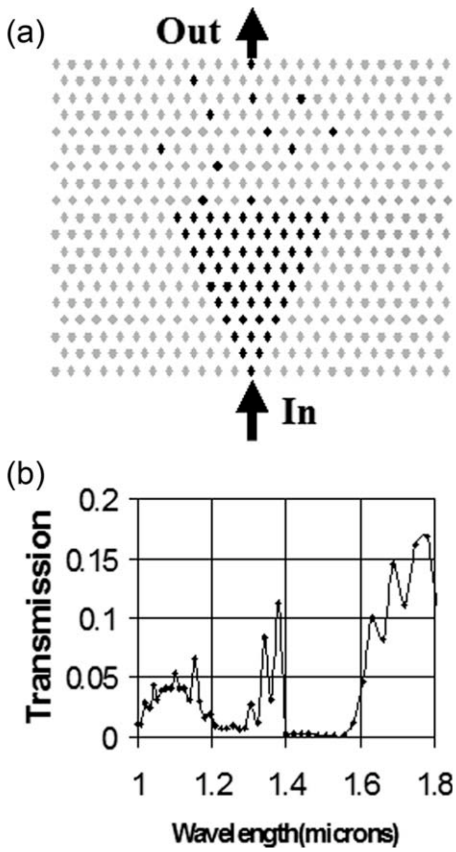

Figure 3 (a) Top view sketch of triangular lattice PC on SOI substrate with a 0.2-μm thick single-crystal Si layer ($n = 3.48$) on a 1.0 μm SiO_2 ($n = 1.45$) layer, with 0.55-μm deep, 0.13-μm radii holes (gray, $n = 1$), and 0.42-μm lattice constant, populated with a pattern of filled holes (black circles, $n = 1.8$) that results in light slowing/delay of 272fs with respect to the same PC with all holes filled. (b) Transmission versus wavelength of (a)

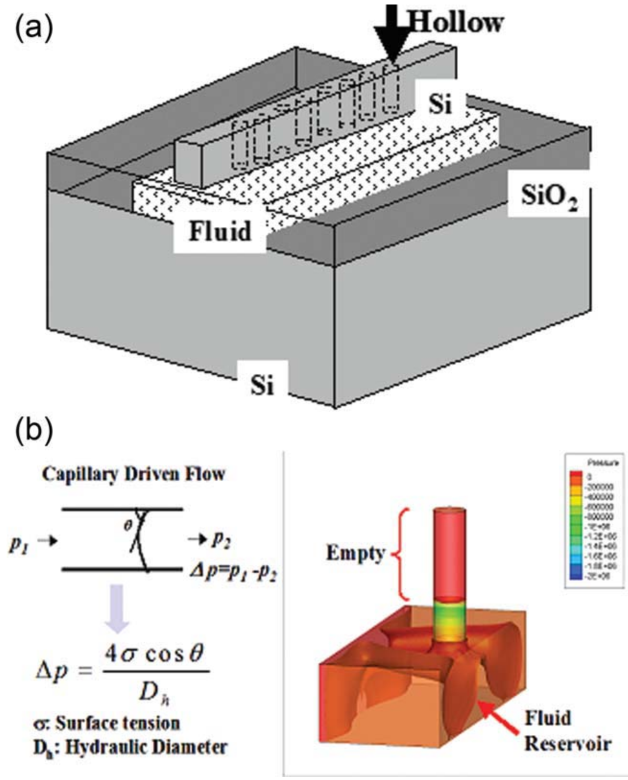

Figure 4 (a) Sketch of implementation of reconfigurable 1-D PC concept. (Top wafer containing nanofluidics layer is not shown.) (b) Nano-channel pressure drop: Water from a reservoir set up under the PC is pulled into the holes by capillary forces. A pressure of MPas must be applied on a working fluid to purge the holes. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

which can only produce kPas of pressure and, thus, are applied to effecting tuning [14, 15], but are not amenable to purging individual holes that enable the general programmability of our approach. The results indicate that hole filling/purging can take place in times of the order of microseconds for 0.75 μm-long cylindrical holes with 0.2-μm (hydraulic) diameter. A number of suitable fluids, with refractive index between 1.76 and 1.846, and transmittances of 99–100% at wavelengths between 1 and 2 μm are available from Cargille™ [19–22].

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SWITCH-MODE POWER AMPLIFIER DESIGN METHOD

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ABSTRACT: *In this letter, it is shown that doctrines behind the devised switch-mode design method investigated by means of simulations for 0.35-μm technology are indeed technology node and application independent. Experimental results verifying this claim are presented for 180-nm SiGe BiCMOS process. Furthermore, a possible expansion of the method is proposed for mm-wave applications.* © 2011 Wiley Periodicals, Inc. Microwave Opt Technol Lett 53:2724–2728, 2011; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26444

Key words: *power amplifier; spiral inductor; BiCMOS; mm-wave applications; computer-aided design*

1. INTRODUCTION

While a lot of time and resources have been placed into transceiver design, due to the pace of a conventional engineering design process, the design of a power amplifier (PA) is often completed using scattered resources; and not always in a methodological manner, and frequently even by an iterative trial and error process, such as seen in Refs. 1–3 for Class-E and Class-F PAs.

In this letter, the methodology developed by the authors for switching-mode [4] PA design (Fig. 1) is revisited. This methodology, based on the set of algorithms (software routine) is devised in such a way that it is technology node independent. Particular care is taken in inductor modelling and the design of monolithic spiral inductors [5]. Successful designs using this method have previously been presented for a 0.35-μm CMOS [6] and 0.35-μm SiGe BiCMOS [7, 8] processes. This letter expands this theory to now include high-frequency BiCMOS processes. Measurement results for a PA design in SiGe 180-nm technology are presented first in order to verify the concepts of technology independence. This is followed by the discussion on how the same methodology can be deployed for PA design for ever-growing millimetre-wave (mm-wave) applications [9].

2. SUMMARY OF THE DESIGN METHODOLOGY FOR RF APPLICATIONS

A new routine-based design methodology for rapid implementation of CMOS and BiCMOS Class-E and Class-F PAs was proposed previously by the authors [6–8]. This methodology is based on the principle that for a given set of specifications, including the PA bandwidth, centre frequency and class of operation (E or F), design equations derived in papers by Sokal and Sokal [10] as well as Raab [11], an optimal lumped-element integrated PA design can be performed in software. For Class-E PA, the design of a series filter topology is performed, allowing for theoretical efficiency of 100%. For Class-F PA, the choice between third-harmonic peaking circuit (three resonators, theoretical efficiency of 81.7%) and the circuit with five resonators (efficiency of 90.5%) is left to the designer using the routine.

The vital strength of the same routine is that the algorithm that determines geometry of the spiral inductor resulting in an optimised quality factor is fully integrated into the routine and is used to design all inductors of the PA. The algorithm, shown in Figure 3 in Ref. 7, is a search algorithm, meaning that a constrained range of geometries is analyzed for the inductance and

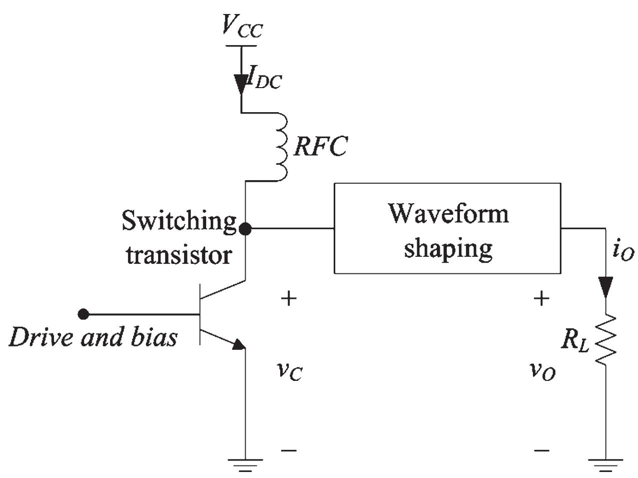

Figure 1 General PA circuit