Integrated Optical Devices Design by Genetic Algorithm

L. Sanchis, A. Häkansson, D. López-Zanón, J. Bravo-Abad and José Sánchez-Dehesa*
Departamento de Física Teórica de la Materia Condensada, Facultad de Ciencias (C-5),
University Autónoma de Madrid, E-28049 Madrid, Spain.
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In this work we use multiple scattering in conjunction with a genetic algorithm to reliably determine
the optimized photonic-crystal-based structure able to perform a specific optical task. The genetic
algorithm operates on a population of candidate structures to produce new candidates with better
performance in an iterative process. The potential of this approach is illustrated by designing a
spot size converter that has a very low F-number (F=0.47) and a conversion ratio of 11:1. Also,
we have designed a coupler device that introduces the light from the optical fiber into a photonic-
crystal-based waveguide with a coupling efficiency over 87% for a wavelength that can be tuned to
1.5 µm.

A new generation of optical devices is envisaged thanks to
the properties of photonic crystals (PCs). Though
the recent advances in three-dimensional PC’s structures,
in the last years much attention has been focused on
systems based on two-dimensional (2D) PC’s because of
their easiness in the fabrication process. Thus, very com-
pact optical devices and circuits can be designed by in-
roducing point and/or line defects. In order to use such
PC circuits in actual applications it is necessary to es-
ablish a connection with an optical fiber. However, the
core of the optical fiber is about one order of magnitude
larger than the PC-based waveguide. Therefore, the de-
sign of an efficient (low loss) spot size converter is a cru-
icial goal in the field of PC; its solution will introduce the
PCs devices in the market place. In this regard, several
groups have tackled this problem by using different
approaches. Most of them proposed tapered waveguide
structures, or by using reflective structures to focus
the light into the waveguide. A different approach con-
sists of using the anisotropy of the PC’s equifrequency
surfaces.

This letter introduces a method that is useful in de-
termining the optimized configuration of a 2D-PC struc-
ture capable of performing a requested optical task with
high efficiency. The method is illustrated by finding a
spot size converter (lens) that has a conversion ratio 11:1.
In addition, the designed PC structure that involves a
spot-size converter in connection with a PC-based wave-
guide it is presented. The insertion loss predicted for this
new structure is about 13%, which is of the lowest re-
ported by numerical simulations based on different cou-
ping mechanisms.

Our method is based on a binary-coded genetic algo-
rithm (GA), an optimization strategy inspired by Dar-
winian evolution. This method has been applied to
solve a wide variety of problems in different fields like,
for example, molecular geometry optimization, material
design, and artificial intelligence. In the field of opt-
ics, the GA has been employed in the synthesis of Bragg
gratings that conform to a particular spectrum, phase
recovering from a fringe pattern, and in designing ir-
regular lateral tapering.

Although our proposal is general and applicable to
any dimensionality, here we analyze 2D-PCs for simplic-
ity. We consider hexagonal lattice of Si dielectric cylin-
ders (nSi ≈ 3.46 at 1.5 µm) in a background of silica
(nSiO2=1.45). We employ the multiple scattering the-
ory (MST) to study the diffraction effects of the TM
modes (in-plane magnetic field) on structures based on
that symmetry. The MST has been successfully applied
by some of us in the analysis of metallic and dielectric
clusters based on 2D PCs.

As the first step in the process, a structure made of a
fixed number of cylinders is chosen. The GA is then im-
plemented with the possibility of removing cylinders, but
it cannot change neither their positions nor their radius.
A string of binary digits represents a possible structure
(individual). Each binary digit (1 means presence and 0
absence of a cylinder at a given position) is called a gene.
Each individual is associated with a value, the fitness,
which is strictly related to the PC property that we are
looking for. A crystal with a good-asked for property
will have a high fitness and vice versa. At start, a cer-
tain number of individuals (population) is created by the
GA that randomly determines their genes. The size of
population P depends on the complexity of the problem,
which is strictly related to the number of genes.

After the initiation, the GA selects two individuals at
random, the one with the highest fitness acts as a parent,
the second parent is chosen in the same way. Now, an
uniform-crossover operator randomly exchanges the chro-
mosomes of the two parents with a probability C and, in
this way, an offspring is created. This is done until we
have a new equal sized population of offspring, i.e. a sec-
ond generation. The selection and crossover operators
tend to enable the evolutionary process to move toward
promising regions of the search space. In a step further,
a mutation operator is introduced to prevent premature
convergence to local maximum. This operator changes
the value of the genes at random with a probability µ. A
high value in the probability of mutation indicates that the GA looks for better solutions at larger distances from a local maximum. The three operators are repeatedly applied to the population, with the constrain that the best-fitted individual is always copied into the next generation (elitism). As there is no way to know if the global maximum is reached, this process is iterated until there is no improvement of the fitness value of the best individual in the population. For further details the reader is referred to books by Hollandand Golberg.

The fitness parameter in our calculations is equal to the component of the Poynting vector, $\vec{S}$, along the propagation direction of the incident beam, which is evaluated in a selected position or in a set of positions depending on the desired result. The Poynting vector is calculated by the MST. The external radiation field is here a Gaussian beam in order to demonstrate the spot-size conversion. The beam is formed as a sum of plane waves weighted with a function dependent of the beam waist radius $w_0$ (see Ref. 15 and references therein). This beam represents the light at the output of a fiber, its diameter $2w_0$ being the diameter of the fiber core (about 8-10 $\mu$m).

Let us deal with the design of the spot-size converter. We assume that a TM polarized Gaussian beam (centered at the origin of our coordinate system) propagates along the $x$-axis. This beam impinges a crystal consisting of a hexagonal array of Si cylinders in silica, the $z$-axis being parallel to the cylinder axis. The size of this crystal along the $y$-direction has to be chosen slightly larger than the incident-beam-width to avoid flux escaping at the lateral borders of the crystal, hence we have chosen a crystal made of 26 rows of cylinders whose total length is about $3w_0$ along the $y$-axis. Regarding its thickness along the $x$-axis, we used 13 columns of cylinders. The total number of cylinders is 318, which is conditioned by our calculation resources. This structure constitutes the lens-material (LM) of our integrated device. We consider a lattice constant $a_{LM}$ and radius $r = 0.294 a_{LM}$. A band structure calculation of the corresponding infinite crystal by means of a plane wave expansion method predicts a forbidden gap for the TM-like modes in the range of frequencies $0.222 - 0.292$ (in units of $2\pi c/a_{LM}$). In order to have a low reflectance device we choose a working frequency of $0.197$; i.e. below the first gap, where property that is difficult to achieve by conventional lens design, its low F-number. According to Gaussian optics, $F=(2\pi)w_0^2/\lambda_0$, which in our lens structure takes a value of only 0.47. On the other hand, the power loss, which is defined as the ratio of the transmitted power calculated inside the focus waist ($2w_0'$) to that of the incident beam, takes the value of 1.0 dB. In other terms, a 79\% of the incident power is squeezed and passes through the focus. At this point let us remain that Kosaka et al. [7] reported a photonic-crystal spot-size converter that reduces the spot-size in the ratio 10:1, but no information is provided about the power passing trough the focus.

Now, let us deal with the problem of designing an integrated device involving the coupling of the light squeezed by the spot-size converted into the PC waveguide. The parameters of the PC of what the waveguide is created, which we name guide-material (GM), must be chosen carefully in order to allow the coupling with a state localized in the waveguide. Firstly, the photonic band structure has to have a full gap at the working frequency of the LM and secondly, a guided mode of the crystal with a missing row of cylinders, must exist at such frequency. Thus, we choose as the lattice parameter of the GM, $a_{GM} = 1.5 a_{LM}$. On the other hand, we keep the same orientation and cylinder radius as in the LM, and the PC waveguide is created along the IK-direction in the hexagonal lattice. Figure 2 represents the TM-bands for the LM along IK as well as the projected band structure of the GM along the missing row of cylinders. It is shown
how the working wavelength $\lambda_0$ of the lens matches a mode in the guided band.

If one simply places the entry of the waveguide at the focal point of the lens, one obtains a total insertion loss as high as 7.03 dB. This efficiency is calculated as the ratio of the total power that is transmitted through the waveguide to the incident power. The optimization process begins at this point by defining a set of 52 cylinders, which are placed in front of the entrance in order to facilitate the coupling to the waveguide mode, and letting the GA operate over it. These cylinders have the same symmetry, lattice parameter and orientation as the GM. The fitness was set equal to the sum of symmetry, lattice parameter and orientation as the GM.

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The simulations by P. Sanchis [2]. References [3] and [4] reported two different tapered waveguides to the incident power. The optimization process begins at this point by defining a set of 52 cylinders, which are placed in front of the entrance in order to facilitate the coupling to the waveguide mode, and letting the GA operate over it. These cylinders have the same symmetry, lattice parameter and orientation as the GM. The fitness was set equal to the sum of symmetry, lattice parameter and orientation as the GM.

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$\lambda_{0}$, +5.2 $a_{LM}$]. Now, each individual has only 32 genes due to symmetry reduction, and just $2^{32} \approx 4.3 \times 10^9$ possible combinations are available. The line (1) in Fig. 3 represents the fitness of the best individual as a function of the number of generations. Each generation contains a population $P$ of 400 individuals. The structure with the best fitness was achieved after 34 generations, the dashed horizontal line defines the maximum value obtained. A resulting power loss of 1.07 dB is obtained, which represents a substantial advance in comparison with the total loss when no mouth-structure was considered.

In order to reduce the insertion loss further, we allow the GA to act over the full structure made of the lens and the mouth. Now, its individual contains 162+32 genes and, consequently, the space search size has been increased up to $2^{162+32} \approx 2.5 \times 10^{58}$. In this case we consider that each generation contains a population of 600 individuals. Figure 3 shows the result of running the GA on this structure, and Fig. 4 plots the optimized integrated device (the wave-guide coupler) together with its electric field modulus pattern. The insertion loss predicted for this structure is as low as 0.61 dB. This means that 97% of the impinging light passes through the waveguide and is detected at the output. In fact, this value is underestimated since it does not include the light reflected at the end of the waveguide by finite size effect. Therefore, the coupling efficiency predicted by this new structure is comparable with the ones reported in the literature. Thus, a waveguide-to-fiber coupling improvement exceeding 2dB per converter is shown in Ref. [2]. References [3] and [4] reported two different tapered couplers that numerically have over 90% power transmission. The simulations by P. Sanchis et al. [5] reported that a transmission over 84% can be achieved if defects are put on a planar photonic crystal tapered waveguide. Finally, the J-coupler proposed by Prather et al. [6] predicts a coupling efficiency of 91%. In spite of the large coupling efficiencies reported for these devices, in comparison with the one here designed, the low compactness and integrability of these devices are their main drawbacks when they are compared with the one designed by evolutionary programming.

Although our simulations involved the simplifying assumption of 2D PC’s, it should be noticed that such 2D-periodic crystals can be studied in actual 3D crystals. For example, our recent simulations of 2D prism re-produces fairly well the behavior of the actual structures in the microwave regime. We conjecture that similar results might also be obtainable in the optical regime by using a PC-slab sandwiched between multilayer films with a large gap. Also, the preceding discussion focused on the TM modes of a structure based on “dielectric-scatterers-on-background”. However, based on the general method presented here similar devices based on “holes-in-dielectric” structures can also be obtained.

In summary, this work has shown that a genetic algorithm used in combination with multiple scattering is able to design photonic crystal-based structures with specific optical properties. By using this approach, we have demonstrated the viability of fabrication of waveguide couplers with low losses and a high spot-size conversion ratio. Besides, they can be integrated in the same wafer with other planar structures in a simple single-step lithographic process. It can be said that this method represents a substantial advance in order to reach the ultimate goal in optical devices design, that is molding the flow of light.

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* Author to whom correspondence should be addressed: jose.sanchezdehesa@uam.es

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FIG. 1. (Left panel) Focusing effect produced by a spot-size converter (lens) based on a 2D photonic crystal (black dots). The pattern of the electric field modulus is represented in a wide spatial region. The length scales are given in terms of the lattice parameter employed in the design of the lens, $a_{LM}$, as well as in terms of the working wavelength of the lens $\lambda_0$. (Right panel) The $x$-component of the Poynting vector represented at the focal point ($x_f=4.60 \lambda_0$). A scale color is used; red (blue) color means maximum (minimum) electric field modulus.

FIG. 2. (Left panel) Photonic band structure of the photonic crystal employed as lens material (LM) along the $\Gamma K$ direction (see inset). (Right panel) Projected band structure of TM modes in the guide material (GM). The grey regions represent the continuum of extended states in the photonic crystal. The white regions are the photonic band gaps. The waveguide is formed by removing one row of Si rods as shown in the inset. The black line defines the guided modes inside the waveguide. The frequencies in both panels are given in reduced units of the respective lattice parameters, $a_{LM}$ and $a_{GM}$. The horizontal dashed line defines the working frequency of optical devices under design.

FIG. 3. Running the genetic algorithm on the lens+waveguide integrated structure. Line (1) defines the fitness of the best structure when the optimization only acts over the cylinders on the mouth of the waveguide, the dashed line defines the maximum fitness achieved. Line (2) represents the corresponding result when the GA acts over the cylinders in the lens and mouth simultaneously. Line (3) being the averaged fitness over the total population in this case. The vertical lines separate the regions where different values of mutation parameter $\mu$ are employed.

FIG. 4. The optimized waveguided-coupler device (dots) obtained by a genetic algorithm. The orange rectangles enclosed the cylinders where the GA is applied. A scale color is used; red (blue) color defines the maximum (minimum) electric field modulus.
Fig. 2. L. Sanchis et al.
FIG. 3  L. Sanchis et al.

- \( \mu = 0.0013 \)
- \( \mu = 0.0026 \)
- \( \mu = 0.0052 \)

Fitness vs. number of generations.
Fig 4. L. Sanchis et al.