Towards a Heralded Single Photon Source Model Based on Photonic Crystal: Constraints and Feasibility

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Abstract
In this paper we present a scheme of a heralded single photon source based on active two-dimensional photonic crystal (PC) over LiNbO3 excited by continuous pump laser source. The use of 2D photonic crystal could improve the conversion light efficiency and obtain height density of mode (DOM) at 1310nm and 1550nm, which will increase the probability of obtaining single photon. The scheme is based on two photonic crystals arranged in serial configuration. The first one acts as extractor of the two wavelengths, and the second as a demultiplexer and can be considered as a time-delay coupler. Also constraints related to manufacturing process are reported in order to show performances of the CP on the heralded single photon source model.
Keywords: *Heralded single photon source, Photonic crystal, Coupler.*

1. Introduction

Quantum information aims to take advantages of the possibilities offered by quantum mechanics to treat information more efficiently [8]. Two main research axes are developed: quantum communications, which provide better security over classic cryptosystem, and quantum computing, which new algorithms based on the principal of quantum mechanics are proposed for reducing the time processing to resolve some problems [7]. The philosophy of quantum communications and quantum processing is developed thanks to q-bit, in classical numeric component and communication systems the unit of information is the bit, but in quantum system the basic unit of information is the q-bit (superposition of states of 0 and 1 (j|0 > +j|1 >). The quantum element easiest to handle is the photon, the value of q-bit depend of polarization of the photon.
To produce quantum application one must generate single photons [12][15], two kinds of sources can be used a heralded single photon source or on demand single photon source.
In this paper we present a model of heralded single photon source based on active two-dimensional photonic crystal (PC) [9], [11], to obtain a single photon emission at 1550nm; this photon is heralded by another photon at 1310nm [14]. The active part of the designed source is the PC. This photonic crystal is based on LiNbO3 doped erbium with a high DOM at 1310nm and 1550nm to improve the interaction between the light and the structure at 1310nm and 1550nm. This photonic structure will be excited by a laser at980nm; outside of the PC we obtain three wavelengths 980nm, 1310nm and 1550nm. The obtained photons are directly injected to another PC acting as a coupler. The two photons are separated and take out through the two outputs of the coupler. A stage of filter can be added in order to eliminate the source laser signal, both remain signals (1310nm and 1550nm) are dissociated borrow different paths, the photon at 1310nm announce and start the detection processes for the photon at 1550nm [13].
Our contribution in this work is three fold: first, we propose a new heralded single photon source model based on active photonic crystal devices. Second, we introduce constraints of manufacturing PC's and relate the behavior of errors on the whole scheme. Third, based on real model, we present results obtained for coupling mechanism for the two generated photons.
The remain parts of this paper are organized as follow: the second section presents the heralded single photon source, in the third section we model the photonic crystal structure which will be the active component of our source, finally we show heralded photonic source and we estimate the efficiency parameters of this model taking into consideration manufacturing introduced errors. Section five concludes this paper.

2. Heralded Single Photon Source

Heralded single photon source is based on important correlation between the emission of the photon and another event. We can't predict when the photon is emitted but we can expect the emission according to the observation of correlated event [2]. As the emission can't be controlled and the photon may occur at any time, a correlated event can be used as an indicator warning the photon emission. In our case, as the PC generates two photons, one photon can be used to announce the other. To describe a single-photon source system, the indicator $g^2(0)$ allows to quantify the single character of photons. This function indicates the relationship of probability to obtain two photons emitted by the source and the probability of having a single photon [4]. A perfect single source has $g^2(0)=0$, it never emit two photons at the same time. The

attenuated lasers have a $g^2(0)= 1$, so, they can't be used as single photon source. Assuming that the source has an average number of photons emitted by a pulse, two worst cases can occur: the first one, when no photon is emitted from the source; and the second one, when more than one photon is emitted. This technique consists of a post-selection of pulses which contains photons and reduce the probability to obtain more than photon in the pulse. For such source, a non linear crystal was used to convert the incident pulses to a photons pairs. Outside of the crystal, we consider that we have a means to separate spatially the two photons of the pair, each photon will follow a different path, the photon (a) will be indicate the presence of photon (b). If we have the presence of photon (a) we have a height probability to receive the photon (b) and low probability to receive two photons. That is why we speak about heralded single photon source, this concept has been introduced by Mandel in 1986. In next sections we present heralded single photon source based on 2D photonic crystal [5] with photon (a) at 1310nm and photon (b) at 1550nm. Fig. 1 illustrates the principal and the architecture of heralded single photon source and summarizes the experimentation principle of the SPS [13]. Photon at 1310 nm is used to herald ones at 1550nm. Two avalanche photodiode detectors APD were used and probability to obtain single photon as a main condition to have the single photon was considered. In [13], authors presented performances in term of probability of a SPDC and NSPDC, (Fig. 2). Authors studied different configurations by simulating photon heralding efficiency vs the probability for a trigger, for different numbers of sources. This probability of obtaining a non-zero photon output the source is taken into consideration in our simulation as an input parameter.
Detectors are used with the same parameters including the probability to detect single photon taking into consideration physical parameters of the APD.

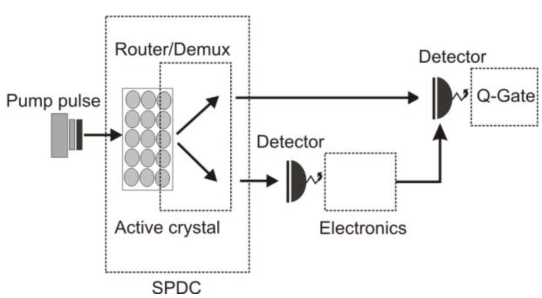


Fig. 1 Heralded Single Photon Source Architecture

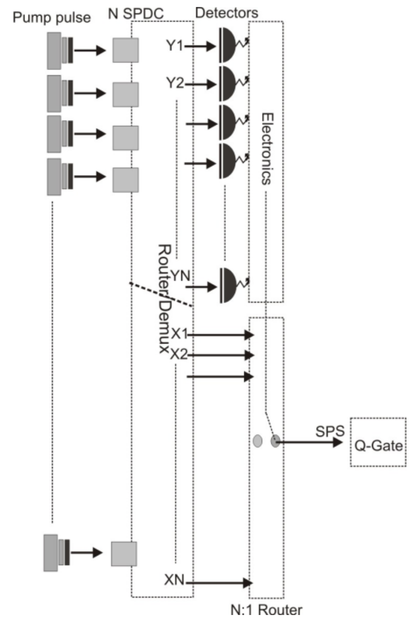


Fig. 2 Heralded Single Photon Source from N spontaneous parametric down conversion (SPDC)

Table I, gives this variation for different number N of SPDC's, according to [13]:

Table 1: Photon heralding efficiency for different number of sources

N_{source}	1	2	4	8	16
P_{hrld}	0,075	0,125	0,25	0,45	0,675
$P_{trigger}$	0,075	0,15	0,25	0,45	0,7

3. Architecture and Performances of Heralded Single Photon Source

The PC converts incident signal (at 980nm) to two signals (at 1310nm and 1550nm). Fig. 3. To separate spatially signals at 1310 nm and 1550 nm, a coupler was used. The photon at 1310nm is used to herald the photon at 1550nm. We use two avalanche photo-diode detectors APD: the first one, used to detect the photon at 1310nm, is always on; the second one detects photon at 1550nm and is used in gated mode. When the first APD detects the photon at 1310nm it starts the second APD during a ΔT period to detecting the photon at 1550nm. In this section we present how obtaining single photons at 1310nm and 1550nm. ΔT is the time detection window; only one photon is required during the ΔT period.
The single photon characteristic depends of the choice of ΔT value and of parameter which is the average ratio of creation of photons pairs (1310 1550nm) by the photonic crystal. The μ_p ratio depends of the power of the laser and

the characteristics of the PC. The average of pairs numbers generated in ΔT is given by (1).

$$\bar{n} = \mu_p \Delta_T \quad (1)$$

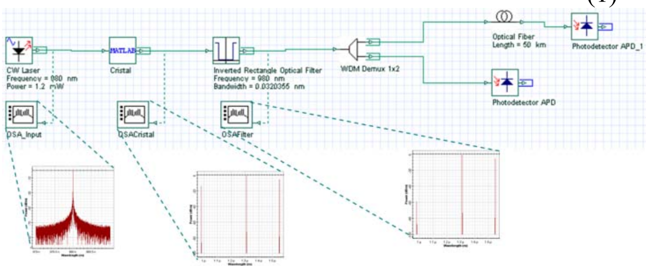


Fig. 3 New heralded SPC architecture

Previously, the light is considered as a wave signal, to present the role of each component of our structure and to study the conversion of the wavelength signal from the laser to the detectors passing by the other components of the architecture. Now, to study the performances of our source and the single photon characteristic, we are interested on the practical nature of light. The principal information and characteristic of our source is the photons number at 1550nm. Here, we analyze the different probabilities P1 and P2 to obtain respectively one photon and two photons emitted by the source. In the photonic crystal we have p the ratio to obtain photons pairs (1310 1550 nm), but not all created pairs in the PC will be collected. γ1310 and γ1550, the lost coefficient of the photons collection, are respectively given by equation 2 and 3.

$$\mu_{1310} = \mu_p \gamma_{1310} \quad (2)$$

$$\mu_{1550} = \mu_p \gamma_{1550} \quad (3)$$

So the probabilities P_1 and P_2 depend of μ_p, γ_{1310} and γ_{1550}. The expression of APD detection ratio S is given in equation 4.

$$S = \eta \mu_s = \eta \gamma_{1310} \mu_{1310} \quad (4)$$

η is the efficiency coefficient of the detector. And all optical detectors are characterized by parameter D_c, dark current when the detector can't detect photons. The detection coefficient noted S^{net} is expressed in equation 5.

$$S^{net} = S - D_c = \eta \gamma_{1310} \mu_{1310} - D_C \quad (5)$$

The probability to obtain no photons generated by the source is given by two cases: the first case the photon at 1310 nm is detected but the photon at 1550 nm is lost express by: $\frac{(1-\gamma_{1550})S^{net}}{S}$. The second case, when the detector has a dark current expressed by: $\frac{D_c}{S}$.

The probability to obtain at least one photon is given by equation 6.

$$P_1^{'} = \frac{(1-\gamma_{1550})S^{net} + D_c}{S^{net} + D_c} \quad (6)$$

Considering the time window ΔT, we can obtain more than heralded photon. The probability to obtain none heralded photons in ΔT is given by equation 7.

$$P_1^{+} = 1 - \gamma_{1550} \mu_p \Delta T \quad (7)$$

Finally, the probability to obtain the heralded single photon is expressed as equation 8.

$$P_1 = \gamma_{1550} \left\{ \left(\frac{\mu_p \gamma_{1310} \eta}{\mu_p \gamma_{1310} \eta + D_C} \right)(1 - 2\mu_p \gamma_{1550} \Delta T) + \mu_p \Delta T \right\} \quad (8)$$

The probability to obtain more than one photon emitted by the source, noted P_2, consists on the presence of the heralded single photon and other none heralded photon. P_2 expression is illustrated in equation 9.

$$P_2 = \mu_p \gamma^2{}_{1510} \Delta T \left(\frac{\mu_p \gamma_{1310} \eta}{\mu_p \gamma_{1310} \eta + D_C} \right) \quad (9)$$

μ_p: ratio to obtain photons pair, depends of the energy of the pulse and the characteristics of the PC;
γ1310 and γ1550: lost coefficient of photons collection;
η : Detection efficency;
D_c: Dark current;
ΔT: Detector time window;
The auto-correlation function is presented in equation 10:

$$g^{(2)}_{(0)} = \frac{2P_2}{P_1^2} \quad (10)$$

μ_{1550} presents the efficiency of photons detections at the crystal exit. As μ_{1550} and μ_{1310} are correlated, we can't increase the value of μ_{1550} without changing the value of μ_{1310}. The value of μ_{1550} affects the probability of P_1. In fact, the increasing of μ_{1550} and μ_{1310} induces an important photon collection productivity, and so on, increases the probability P_1 and P_2 to emit one photon or more by the source. But, this parameter don't affect $g^2(0)$. μ_p affects $g^2(0)$ more than the P_1. When μ_p is increased, $g^2(0)$ also growths. The value of μ_p must be chosen as a lowest value which gives single photon emission. The detection process is not directly linked to the creation of photons pairs, but the characteristics of the detector affect the efficiency of the single photon source. Increasing the dark current D_c, decreases the probabilities P_1, P_2 and increases P_0. The period ΔT is important to obtain only one photon in the gate, decreasing ΔT don't disturb the probability P_1 but decreases P_2. In practice, the choice of ΔT is important to ensure the presence of only one photon in the gate.

4. The Photonic Crystal Model

4.1 The active photonic crystal

To develop a heralded single photon source, we design an active component which will generate a photon pair; existing works use one dimensional Bragg structure based on nonlinear structure excited by laser pulses. In this work we use a two dimensional photonic crystal based on a non linear crystal LiNbO3 doped Erbium.

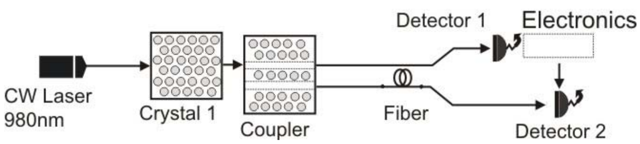


Fig. 4 Stages of the SPS

In the majority of studies, researchers try to control the wide and the position of the photonic band gap [10]. They show, that by using photonic crystal with triangular arrangement, we obtain large band. On the other hand, the important influence motif radius and geometrical structure periodicity was proved. The r/a ratio is used as a correlation factor that influence strongly diagram band variation in terms of wide and central wavelength band. By using FDTD method, we model a 2D photonic crystal with triangular arrangement of air holes. Over LiNbO3 substrate. To choice the geometrical parameters of the structure, we must consider two conditions. The first is to fix the two wavelengths (1310nm and 1550nm) on the boards of the photonic band gap (PBG) to obtain a height density of modes at 1310nm and 1550nm. The second condition is the constraint realizable parameters of LiNbO3.

On the PBG diagram we have on standard frequency. We calculate the radius and the period to obtain the wavelengths 1310 nm and 1550 nm on the border of the PBG. The first border of the PBG is on 0,323 and the second is on 0,381. The obtained results of r and a permit to put 1310 nm and 1550 nm wavelengths on the border of PBG, the energy bands limited the PBG are flat. This kind of energy bands induces height coefficient of DOM. So there is an important interaction between the materiel and the light. With our proposed structure we obtain more coefficient of light extraction at 1310 nm and 1550 nm. This structure of the photonic crystal makes easier the conversion of laser impulsion to a photons pairs.

Table 2: Parameters of the structure

a(nm)	*r(nm)*	*Array lattice*	*Number of low*
700	280	Trianguler	10

As shown in the fig. 5, we have an important wide of photonic band gap in TM modes with r/a = 0,4.

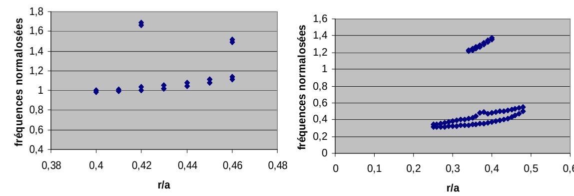


Fig. 5 Width of the PBG vs different ratio r/a in TE mode (left) and TM mode (right)

We study in fig. 5 the effect of the polarization and variation on the behavior of the PBG. In TM mode, a PBG is obtained when the ratio r/a is between 0,3 and 0,4. Calculation of the diagram band for TM mode and r/a= 0,3 are illustrated in fig. 6.

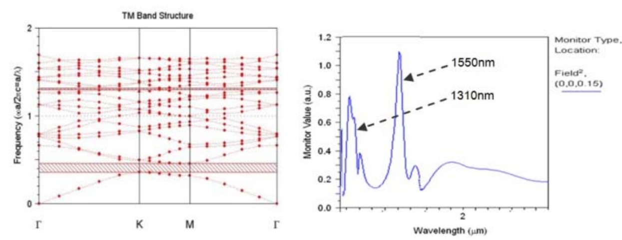


Fig. 6 Band diagram of the PC (left) DOM of the structure (right)

A simple comparison between 1D and 2D photonic crystal DOM, show that the 2D DOM is twice that 1D. When we increase the DOM value the production of photons pair's factor ¸t_p will be increased. With 1D photonic crystal¸ μ_p = 6,6106 s^{-1} [2].With our model (based on 2D photonic crystal) ¸ μ_p = 12,2 s^{-1}. We will see that this value will increase the probability P_1 to obtain one single photon.

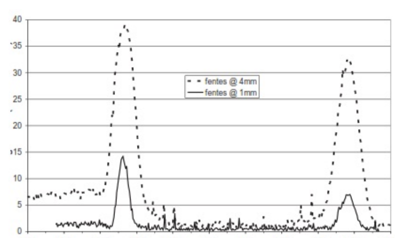


Fig. 7 Density of mode of one dimensional photonic crystal LinbO3 doped Erbium

This comparison is shown on fig. 6 and fig. 7.

4.2 Manufactured profile structure

In this section we introduce an example of obtained profile structure. First, we focus on the irregularity of the hole perimeter. Process of fabrication introduces some defects to the sample: Variation and irregularity of PC period, Variation and irregularity of holes radius and deformation of holes shape. In this case, we observe an error in order of 20 nm for the radius of holes and 40 nm for pitch combined with irregularity and deformation of shape causes the modification of the PC's properties. Different profile of the circumference are obtained, the study can't be determinist. Our approach consists of measuring the maximum radius of the irregularity and the minimum one. This is when the average of the obtained holes has a pseudo-circular shape.

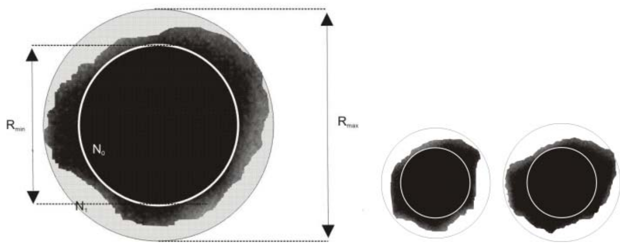
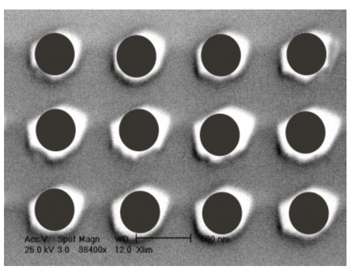
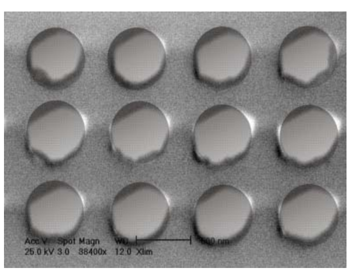


Fig. 8 Irregular perimeter profile

Fig .8 show the cases of shape defect obtained after fabrication. In the case of rectangular lattice, fig. 8, shows the approximated maximum and minimum radius and the pitch variation presented as the distance between hole centers in the case of circular profile.



(a) Circular defect internal transposition



(b) Circular defect external transposition

Fig. 9 Internal and external transposition

The profile of obtained holes were digitized as a function of the (x) and (z) directions. The accuracy of digitization was chosen equal to 0,1 µm. The digitization step choice through (x) and (z) was fixed depending of the hole dimensions (diameter and pitch). The diagram band of the fabricated PC don't much with modeled PC one. In the TM polarization, we note that in the real PC, the wavelength 1550 nm chosen don't belong to the PBG.

This band is the result of interference phenomena causes by the modulation of refractive index. Defects introduced by fabrication process will break crystal's periodicity that will change the dispersion behavior of the structure.

4.3 Photonic crystal waveguide coupler

In this section, we present results of simulation applied to a switch device based on a non perfect photonic crystal structure. We present the behavior of waited operation by a direct comparison with ideal structure. We focus on only three parameters switch efficacy, transmittance and output spectral width. In order to investigate the dynamic of the proposed coupler structure, it is important to consider the basic component of the device: the 2-D waveguide, made by removing a column from a square lattice of infinitely dielectric rods surrounded by air [3], [6], [10]. The rods are assumed to have circular cross-section with a radius, where is the rod-to-rod pitch.

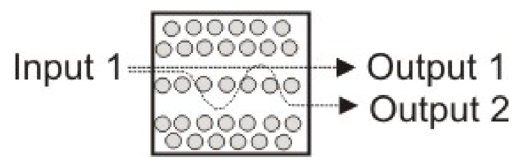


Fig. 10 PC waveguide coupler for single photonic source

The PC coupler is to use to allow the separation of both wavelengths. Structure will allow the wavelength of 1310 nm to take release through Output1. The wavelength of 1550 nm follows the way 2 (Output2) (fig. 10). The length L of the coupler will fix the number of oscillations between both defects of the guide. In our case L is chosen to allow a single oscillation.

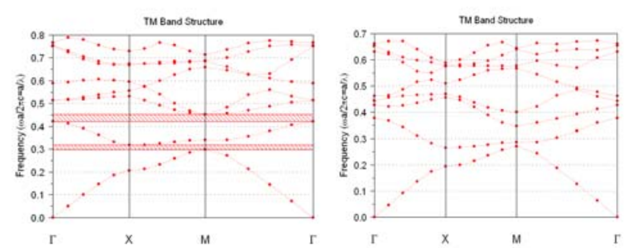


Fig. 11 PC Diagram band for ideal profile structure (left) and real profile structure (right)

This important dielectric contrast is recommended since it enables large photonic band gap (PBG) [17]. Performing numerical calculations for this perfect square lattice, we find that the structure has a PBG for the Transverse Magnetic (TM) modes ranging from 0,2875 to 0,4221 in normalized frequency units, being the free-space wavelength. To create the directional coupler, two parallel waveguides are set along the directions which are separated by either one dielectric rod (Fig. 11). The super cell must include the two linear defects corresponding to the two coupled waveguides in order to implement the device structure.

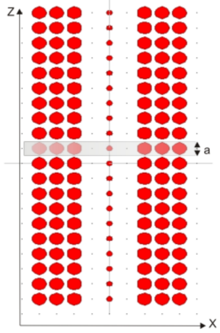


Fig. 12 Schematic view of the studied 2D photonic crystal coupler

4.4 Performance in wavelength dependent application

The coupling process is explained by considering the super modes that the two nearby guides may support. These modes, with β_{even} and β_{odd} parity, have different propagation constants even and odd respectively. The beat length L_β, through which the coupling occurs, and the coupling coefficient κ are defined as follow:

$$L_B = \frac{2\pi}{\Delta\beta} = \frac{2\pi}{|\beta_{even} - \beta_{odd}|} = \frac{\pi}{\kappa} \qquad (11)$$

The coupler is said in cross when its length is an odd multiple of $L\beta/2$. The field injected into one waveguide switches entirely to the other one. However, the coupler is in bar state when its length is an integer multiple of the beat length. In this case, the field comes out the input waveguide. A photonic coupler with a given length L, may act as a channel inter leaver in WDM communication system since the propagation constants difference Δβ varies as a function of waveguide.

The black filed regions correspond to the extended modes lying in the infinitely square lattice, in absence of any defect. The area between the bottom and the top of these zones forms the pseudo band-gap. Regarding the symmetry plane between the two waveguides, there are both even and odd modes at every given frequency. To provide a complete power transfer from one waveguide into the other, both an even and an odd mode must propagate simultaneously. In our cases, for the coupler of fig. 13 (left), it occurs for the spectral range $0,3433 < a/\lambda < 0,4434$ while for that of fig. 13 (right), it happens for $0,3094 < a/\lambda < 0,247$.

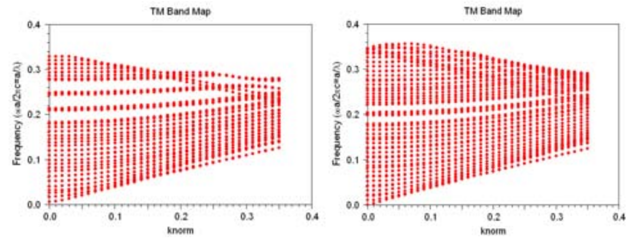


Fig. 13 Dispersion diagram of the coupler PC real (left) ideal (right)

It can be seen that when the interaction region between the coupled waveguides is wider, the beat length increases exponentially when the frequency rises. These important values of (L_B/a) lead to very small coupling coefficients. However, for the case of two nearby straight guides, we notice that the beat length decreases with increase in the wavelength. This can be explained by the fact that as the wavelength is increased, it becomes easier for the wave to cross the barrier leading to stronger coupling and hence smaller coupling length. Therefore, a wider common wall leads to a lower coupling and hence to a more equalized propagation constants for even and odd modes. The beat length increases significantly and the coupling coefficient is very small. Nevertheless, when the difference between the propagation constant of both modes increases, the coupling length decreases which means that a higher coupling coefficient is achieved. Since, the main goal is to strengthen the coupling so it will be interesting that the two cores are closer to each other, like the coupler of Fig. 12. On the other hand, if we observe carefully the values reached by the beat length, we can conclude that it lies in the micrometer range, which thereby, reduces the coupler length as compared to the conventional directional couplers, which falls in the millimeter range. If we deal with a given frequency, it is possible to derive the beat length from the dispersion diagrams. We find the propagation constants for both even and odd modes referring to the selected wavelength λ_0. Then, we compute the beat length according to the expression 11. For example, we consider the frequency $a/\lambda = 0,35$ and we try to find the beat length for the two kinds of couplers. For the coupler of Fig. 12, the corresponding beat length equals: L_B=5,63 λ_0. This result is illustrated in the Fig. 14(left). Thus, complete switching from one guide to the other requires only a path as short as three wavelengths. Concerning the second coupler depicted in Fig. 14 (right) the corresponding beat length is equivalent to: L_B=21,74 λ_0.

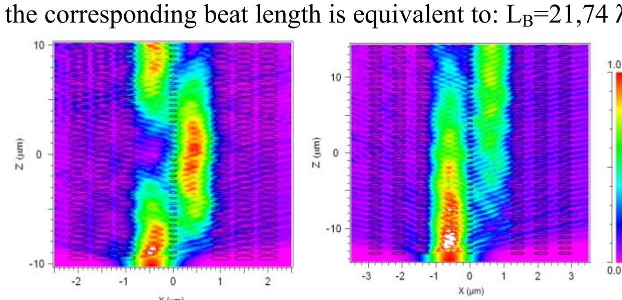


Fig. 14 Field evolution into ideal (left) and real (right) structures

For the coupler/demultiplexer based on photonic crystal we obtain in the bad case 70% of transmittance. Then we obtain γ_{1310} = 0,7 better then classical coupler/demultiplexer γ_{1310} = 0; 47 [2]. With the 1D photonic crystal and classical coupler/demultiplexer P_1= 0,4 [2]. In our model we have increase the value of μ_p and γ_{1310} then improve the P_1= 0,5748.

5. Conclusions

In this paper we presented new architecture of a heralded photonic active crystal allowing having a height efficiency coefficient around 70%. The second component which we presented being a coupler based on photonic crystal, allowing the control of wavelengths separation. A comparative study between ideal and real cases was led to demonstrate the sensibility of this operation considering constraints of manufacturing. The study of the geometrical constraints of the coupler, has allowed demonstrating the sensibility of demultiplexing operation and its total dependence considering the chosen parameters. With the proposed architecture, we were able to reach the value of P_1= 0,5748 to have a single photon. In a future work, we shall study time-delay introduced by the coupler in its switching configuration to be able to control ΔT window of 1550 nm detection. Also it will be interesting to integrate into the simulation the filter characteristics which will be insert between both CP.

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