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Circuit model for efficient analysis and design of photonic crystal devices

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Abstract
We substitute different types of photonic crystal waveguide components by approximate transmission line circuits. The proposed distributed circuits exploit the analogy of wave propagation in photonic crystal waveguides and transmission lines. They are either cascaded to each other or inserted like stubs to imitate wave propagation within the photonic structure. Notable examples, e.g. coupled waveguide-cavity systems, sharp 90° bends, and T-junctions, are studied in detail. It is shown that analysis of the proposed circuits here can yield accurate enough results and thus substitute the brute-force numerical methods. The privilege of having analytical models is exploited to improve the performance of sharp 90° bends and T-junctions. The presented results are verified by using the standard finite-difference time domain (FDTD) method.

Keywords: integrated photonics, photonic crystal waveguides, circuit theory

1. Introduction

Since the discovery of photonic crystals (PhCs), several physical effects such as the photonic band gap, superprism effect, negative refraction, slow light generation, and Cerenkov radiation generation have been demonstrated on them [1–5]. PhCs are also used to realize many optical devices, such as waveguides, resonators, filters, optical switches, and power splitters [6–10]. These devices are analyzed by numerical methods such as FDTD, the time domain beam propagation method [11], the multiple multipole method [12], and the Dirichlet-to-Neumann method [13]. Despite their generality and flexibility, these approaches require massive calculations and give little insight into the physics of the devices. Therefore, circuit models, which provide both computation efficiency and physical insights, are of great interest, especially for synthesizing devices [14–17]. They bring the concepts and standard design methodologies of microwave engineering to PhCs and thereby improve our design ability.

We have recently reported circuit models for designing matching stages for (i) light coupling into PhCs [18], (ii) mode extraction in PhC waveguides [19], and (iii) PhC cavities [20]. More recently, these models have been applied to optical filter designs using stubs in PhC waveguides [17]. This work aims to develop a more unified and generalized circuit model, based on previous works, for modeling different structures. Thus, the slightly modified stub model [17] and cascade model [20] are presented for this purpose. It is demonstrated that by appropriately using these two models different configuration and devices created in PhC waveguide can be efficiently analyzed and optimized.

The proposed circuit model is applied to three different structures. First, a coupled waveguide-cavity system that exhibits the Fano resonance [21, 22], is examined to demonstrate the model's accuracy in predicting the structure's behavior. Second, a sharp 90° bend, an important element in many devices, is studied and it is shown, by using the proposed model, that a slight displacement of one rod can significantly decrease the bend loss. Finally, a T-junction is modeled and a simple matching stage is designed to enhance the amount of power transmitted to each branch of the junction.

This paper is structured as follows. In section 2, the circuit model for cascade and stub-like structure is described. In section 3, the proposed circuit model is used for a coupled waveguide-cavity system. Sharp bends and T-junctions are investigated in sections 4 and 5, respectively. Finally, the conclusions are made in section 6.

2. The circuit model

In this section, details of the proposed circuit model are presented. The main idea of this circuit model has already been explained in previous studies [17–20]. Here, these works are unified and slightly modified in order to obtain a generalized model which can be applied to more complicated structures. First, a cascade model is presented for a PhC waveguide varying in the propagation direction, then the stub model of [17] briefly reviewed with slight modifications.

When different parts of the structure are in series, the cascade model is used. So, each part is modeled with a transmission line and then series parts are considered as cascaded transmission lines. However, in many cases, for a square lattice PhC, some parts of the structure are perpendicular to each other. In such cases a direction is chosen as the main direction and then the perpendicular parts are modeled as a stub. In this section, the circuit model of a single stub is presented and then used in different structures.

In the proposed circuit model scalar impedances and propagation constants are used. It is shown elsewhere [23] that a scalar model is not sufficient for a PhC structure. However, in many practical cases a scalar model can provide a good approximation [18]. In the following subsections, we explain the limitations of the model.

2.1. Cascade model

Consider the configuration shown in figure 1(a), in which a line defect PhC waveguide is illustrated. The PhC is a square lattice of rods with a lattice constant of a. The size of defect rods varies in the propagation direction, z. To develop a model for this structure, a transmission line is attributed to each section as depicted in figure 1(a). The left and the right waveguides are simple PhC waveguides, formed by removing a row of rods from the complete PhC. The propagation constant of the corresponding transmission lines, β_{W}, is made equal to the propagation constant of the PhC waveguide, and its characteristic (Z_{W}) impedance assumed to be equal to 1. Therefore, the impedance of the other sections is normalized to Z_{W}. It should be mentioned that the propagation constant of the PhC waveguide can be found efficiently using the transmission line model [19], although numerical methods such as FDTD can also be used to extract this parameter. The first limitation is imposed here by attributing a scalar impedance and propagation constant to each part of the structure. So one and only one guided mode is allowed to be excited in the PhC.

The PhC waveguides created by periodic repetition of the corresponding section should be analyzed to determine the propagation constants of the other transmission lines. For example in figure 1(a), β_{C} is the propagation constant of the PhC waveguide of figure 1(b), which is created by the periodic repetition of the central section. To calculate Z_{C}, the zeroth-order reflection coefficient (R) from a semi-infinite

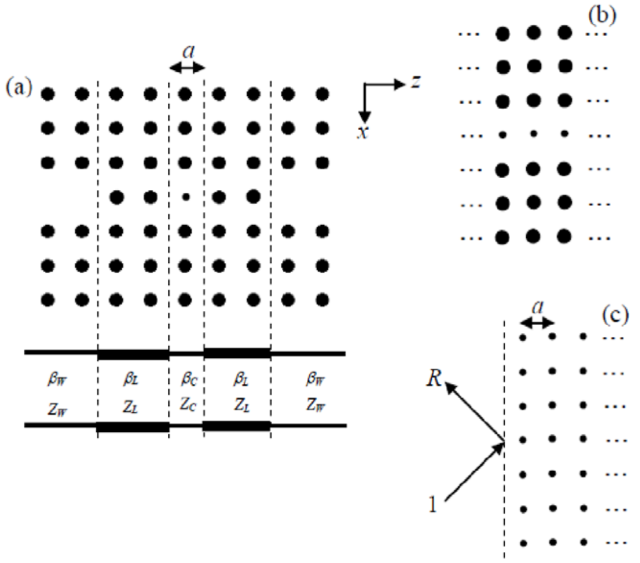

Figure 1. (a) A PhC waveguide varying in the propagation direction and its transmission line model. (b) Line defect PhC waveguide for extraction of the middle transmission line propagation constant β_{C}. (c) The semi-infinite PhC whose reflection coefficient yields Z_{C}.

square lattice PhC with lattice constant of a has to be computed. The radius of rods in this PhC is the same as in central region (see figure 1(c)). The structure is illuminated with a uniform plane wave with the z component of its wavenumber being $\beta_{\mathrm{W}}(\omega)$, where ω is the working frequency. In this paper, the Legendre polynomial expansion method is employed to extract diffraction orders and their reflection coefficients [24]. The MATLAB code for this method is available at http://ee.sharif.edu/~ khavasi/index_files/LPEM.zip.

Given the reflection coefficient, $R(\omega, \beta_{\mathrm{W}}(\omega))$, Z_{C} can be easily obtained using the following relation:

$$Z_{\mathrm{c}} = \frac{1 + R(\omega, \beta_{\mathrm{W}}(\omega))}{1 - R(\omega, \beta_{\mathrm{W}}(\omega))} Z_{\mathrm{W}}. \quad (1)$$

It is clear that this impedance definition is based on the zeroth diffracted order, hence the second limitation is that the other diffracted orders must be in cut-off.

In finding $R(\omega, \beta_{\mathrm{W}}(\omega))$, the transfer matrix of each PhC layer is computed, and the normal component of the Bloch wavenumber κ_z can be easily extracted [3]. Interestingly, this can be a good approximation of β_{C}, the propagation constant of central transmission line. This approximation is preferred, especially when the wave is not propagating, because its calculation is simpler and its inaccuracy does not affect the results substantially.

The characteristic impedance and the propagation constant of the two remaining transmission lines (i.e. Z_{L} and β_{L}) can be calculated by following the same procedure as for obtaining Z_{C} and β_{C}.

2.2. Stub model

In section 2.1, a circuit model was developed for a cascade structure, however the structure can have stubs in the

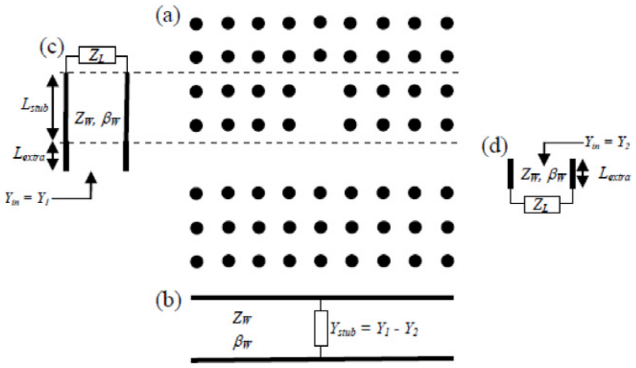

Figure 2. (a) A PhC waveguide with a terminated stub whose length in this structure is $L_{stub} = 2a$. The admittance of the stub is $Y_{stub} = Y_1 - Y_2$. (b) The transmission line circuit model for the structure. (c) The loaded transmission line whose input admittance is $Y_{in} = Y_1$, and (d) the loaded transmission line whose input admittance is $Y_{in} = Y_2$.

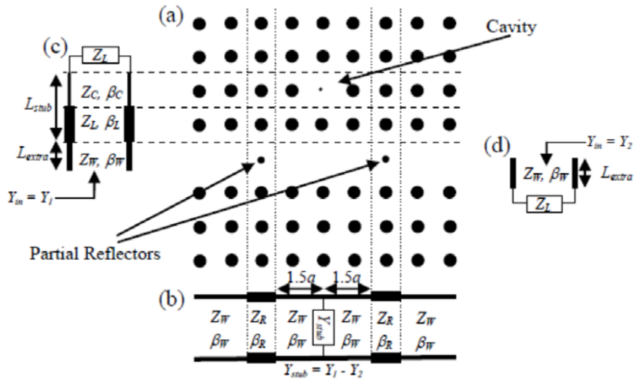

Figure 3. (a) A structure with a side-coupled cavity and two small partial reflectors within the PhC waveguide. (b) The proposed circuit model for the structure in which the cavity is modeled with a stub and the cascade model used for partial reflectors. (c) The loaded transmission line whose input admittance is $Y_{in} = Y_1$. Different parts of this transmission line are obtained by using the cascade model. (d) The loaded transmission line whose input admittance is $Y_{in} = Y_2$.

perpendicular direction in many configurations. A simple case is the structure shown in figure 2(a), in which a stub with length $L_{stub} = 2a$ is created by removing two rods from one side of the waveguide. The circuit model for this structure is depicted in figure 2(b). The effect of the stub is modeled with a shunt admittance in this circuit, $Y_{stub} = Y_1 - Y_2$, where Y_1 and Y_2 are the input admittance of the two circuits shown in figures 2(c) and (d), respectively [17].

The normalized load impedance Z_L represents the impedance of the semi-infinite PhC with the stub terminated to it.

The in- and out-coupling of light back and forth between the PhC waveguide and the stub imposes a certain phase delay. Hence, a logical suggestion for L_{extra} is to set it proportional to the inverse of the propagation constant. Thus, it is written as $L_{extra} = \phi/\beta_W$, where ϕ is a constant to be numerically obtained. To find ϕ, a FDTD simulation for one structure with arbitrary stub length has to be done and then ϕ is tuned in a way that the results of the transmission line model becomes as close as possible to the FDTD results. It should be emphasized that for a given PhC this tuning process is done only one time and then the obtained ϕ is applicable for any configurations carved in this PhC.

The PhC which is considered throughout this paper is a square lattice of dielectric rods in air. The radius and the permittivity of the rods are assumed to be $r = 0.2a$ and 11.56, respectively, where a is the lattice constant. For this PhC, choosing $\phi = 0.45$ leads to relatively accurate results.

It should be emphasized that the stub model has the same limitations as those mentioned for the cascade model.

3. Coupled waveguide-cavity system

Coupled waveguide-cavity systems are widely used for realizing PhC devices [6, 7, 9, 22]. For instance, a cavity which is side-coupled to a PhC waveguide and small partial reflectors in the waveguide lead to sharp asymmetric resonances known as Fano resonances. The transmission in this kind of resonance varies sharply from 0% to 100%, so it can be employed for optical bistability devices, optical switches and optical sensors [22]. The Fano resonance asymmetry is generated from a close coexistence of resonant transmission and resonant reflection [21], which is due to the interference between a direct and a resonance-assisted indirect pathway. Constructive interference corresponds to resonant enhancement and destructive interference to resonant suppression of the transmission [21]. The presence of the direct pathway is an essential aspect of the Fano effect.

In this section, the proposed circuit model is applied to a coupled waveguide-cavity system strongly similar to the structure studied in [22]. As shown in figure 3(a), the structure studied here is a PhC waveguide side-coupled to a cavity. The waveguide is made by removing a row of rods from the PhC introduced in the previous section and the cavity created by reducing the radius of a rod to $0.05a$. Two rods with radii of $0.1a$ are introduced to the side-coupled structure in order to provide partial reflection for the waveguide mode. The distance between the reflectors is $4a$ and they are placed symmetrically with respect to the cavity. The proposed circuit model is illustrated in figures 3(b)–(d). The parameters of this circuit can be computed by following the method described in section 2.

The accuracy of the proposed model is tested by comparing it with FDTD in figure 4. In this figure the transmission is calculated by a two-dimensional (2D) FDTD [25] (circles) and the proposed circuit model (solid line) plotted versus the normalized frequency $\omega_n = a/\lambda$, where λ is the free space wavelength. A Fano resonance can be observed at $\omega_n = 0.366$ whose frequency and shape are predicted well by the proposed model.

4. Sharp 90° bend

It has been demonstrated that a PhC waveguide can guide light with great efficiency around a sharp corner [26, 27]. Numerical simulations reveal very high transmission (>95%)

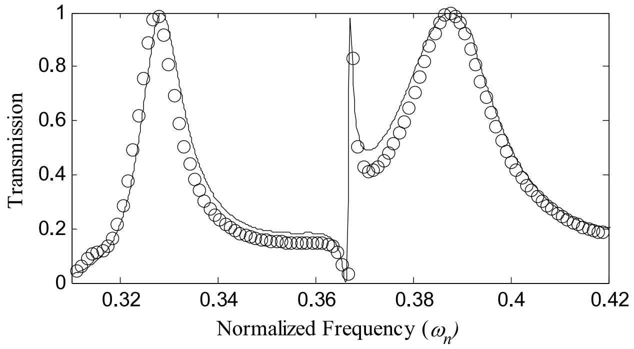

Figure 4. The transmission of the structure shown in figure 3(a) as a function of the normalized frequency, obtained by FDTD (circles) and the proposed transmission line model (solid line).

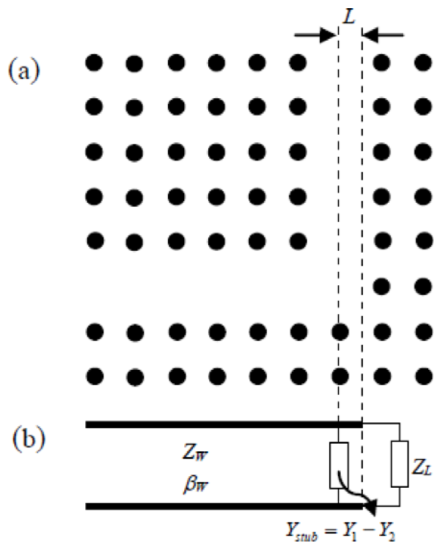

Figure 5. (a) A sharp 90° bend and (b) its equivalent circuit according to the proposed model.

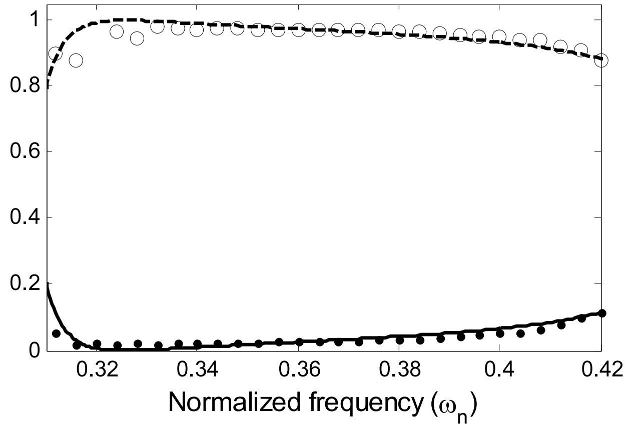

Figure 6. Transmitted (dashed line) and reflected (solid line) power versus the normalized frequency for a sharp bend computed by the proposed model. FDTD results for transmission (circles) and reflection (dots) are also shown.

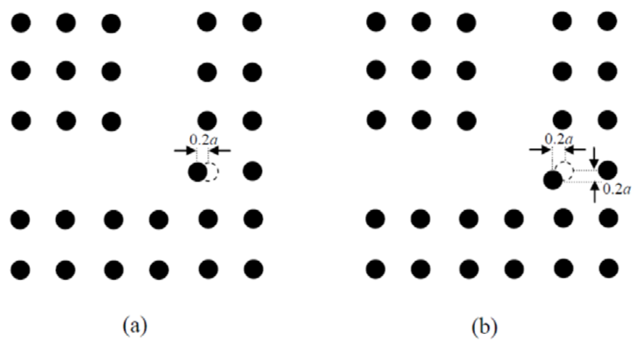

Figure 7. (a) Moving the rod at the end of the bend 0.2a leftwards reduces L to 0.3a which improves the bend performance. (b) Further improvement is achieved by moving the rod 0.2a downwards.

over wide frequency ranges [26]. In this section, it is shown how the proposed circuit model can be used for obtaining transmission characteristics of a sharp bend. Moreover, based on the circuit model, a simple modification is applied to the bend, which results in almost complete transmission (>99%) over wide frequency ranges. Optimization of the 90° bend has already been achieved by numerically changing the radius of several rods [12, 28]. Here, the improvement is obtained by relocating only one rod.

A sharp bend in a PhC waveguide and its equivalent circuit are illustrated in figures 5(a) and (b), respectively. In the proposed circuit model, the vertical waveguide is considered as a stub. On the other hand, the horizontal waveguide has been terminated to the semi-infinite PhC whose impedance is Z_L. The distance between the center of the stub and the interface of the semi-infinite PC is $L = 0.5a$, and thus the same distance between the load impedance Z_L and the stub shunt admittance Y_{stub} is assumed in the equivalent circuit. Since the vertical waveguide is not terminated, it is clear, according to figure 2(c), that $Y_1 = 1/Z_W$. On the other hand, Y_2 is exactly the input admittance of the circuit shown in figure 2(d).

Let us examine the accuracy of the proposed equivalent circuit in a numerical example. Consider a bend that is created in the PhC whose parameters were given in section 2. The transmission (dashed line) and the reflection (solid line) from the bend, computed by the proposed model, is plotted in figure 6 versus the normalized frequency. For the sake of comparison, the transmitted (circles) and reflected (dots) power obtained by the 2D FDTD [25] are also plotted in this figure. It can be seen that the results of the proposed model are in good agreement with those of the FDTD.

Reflection loss can be reduced by adjusting L. Indeed, using the circuit model, it can be shown that a significant loss reduction in a wide range of frequencies can be obtained by choosing $L = 0.3a$. In order to decrease L in the structure, one can move the rod at the end of the horizontal waveguide towards the left. For $L = 0.3a$, the displacement should be 0.2a, as illustrated in figure 7(a). The reflection of the bend, computed by FDTD, after and before this modification is shown in figure 8 with squares and circles, respectively.

Further reduction of reflection loss can be achieved by moving the rod 0.2a downwards, as shown in figure 7(b). This displacement leads to better shaping of the bend curvature.

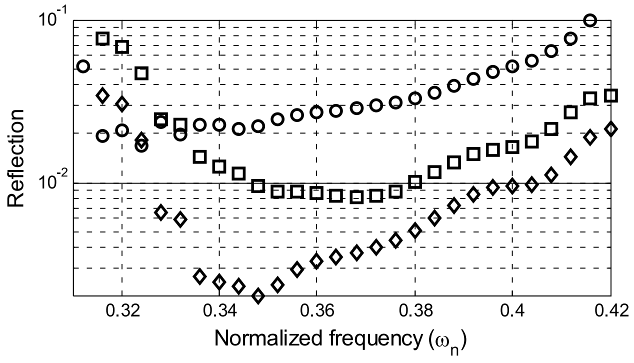

Figure 8. The reflection of the structures of figure 5(a) (circles), figure 7(a) (squares) and figure 7(b) (diamonds) obtained by FDTD.

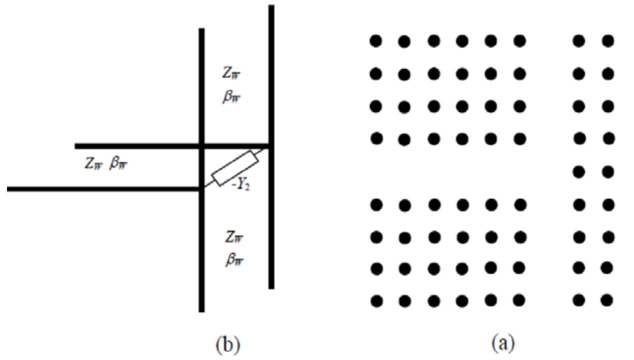

Figure 9. (a) A T-junction in a square lattice PhC and (b) its circuit model based on the stub model.

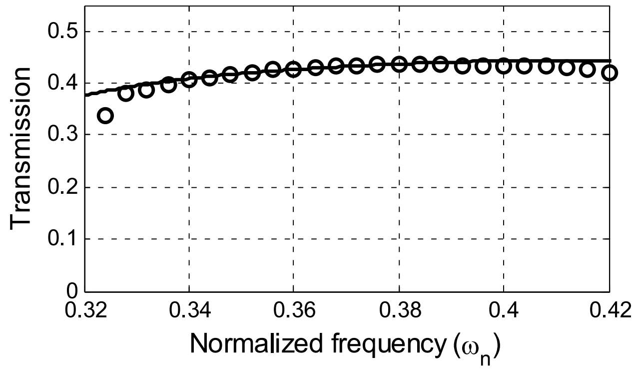

Figure 10. Transmission spectra of T-junction shown in figure 9(a) was obtained by the circuit model (solid line) and FDTD (circles).

The reflection of this structure obtained by FDTD is depicted in figure 8 with diamonds. It can be seen that in wide range of frequencies ($\omega_n = 0.327$–0.405), the reflection is less than 1%. The proposed model cannot explain how the second modification (downward displacement) improves the bend performance. However, it may be justified by the geometrically improved shape of the bend after this modification.

5. T-Junction

A T-junction plays an important role in integrated photonic circuits. Moreover, a T-junction can be used as a power splitter that splits the input power into the two output waveguides without significant reflection or radiation losses [1, 10, 29]. In this section, the proposed circuit model is applied to a T-junction. It is also proved that the reflection is at least 11.1% for a simple T-junction. However, we achieve low reflection loss (<4%) in a wide range of frequencies by designing matching stages.

A T-junction in a square lattice PhC is shown in figure 9(a). To develop a circuit model for this structure, the horizontal guide is assumed as a stub in the path of the vertical guide. Now, by applying the stub model described in section 2, the circuit model illustrated in figure 9(b) can be easily obtained. As can be seen, this circuit is composed of three identical transmission lines joining each other at the junction. The admittance $-Y_2$, where Y_2 is the input admittance of the circuit shown in figure 2(d), is modeling the effect of the reactive power stored in the junction.

The transmission from one of the vertical ports is plotted in figure 10. The results are obtained by using the proposed model (solid line) and FDTD (circles). It can be seen that the transmission is always less than 44%. This can be easily explained by the proposed circuit model. Let us, in the best-case scenario, neglect the effect of $-Y_2$, so the input (horizontal) waveguide meets two identical waveguides at the junction. Hence, the impedance seen from the input port is $Z_W/2$, which is the equivalent impedance of two parallel lines with an impedance of Z_W. This leads to the mismatch of impedances and at least 11.1% of the power will be reflected and the maximum attainable power in each output port will be at best 44.4%. However, as is seen in figure 10, the situation is worse in the practical case because of the presence of the admittance $-Y_2$.

The above-mentioned argument reveals that the performance of the structure can be improved by designing a matching stage. To this end, a structure similar to what is shown in figure 11(a) is proposed, in which two rods are inserted to the output ports. As described in section 2, the regions where the rods are placed can be modeled with transmission lines whose impedance and propagation constant are denoted by Z_r and β_r, respectively.

It is well known from transmission line theory that the impedance of a one-layer matching stage should be geometrical mean of the two sides. Therefore, for the special PhC which is considered here, Z_r should be $Z_W/\sqrt{2}$ (geometrical mean of Z_W and $Z_W/2$), which corresponds to a rod whose radius is about $r = 0.07a$ (i.e. the PhC whose parameters were given in section 2). Interestingly, Fan *et al* proposed the same value for the radius of this rod, though their approach was numerical. Using the coupled mode theory argument, they qualitatively concluded that decreasing the coupling between the resonance and the output waveguides can improve the performance of the structure. Then, they numerically (using FDTD simulations) found the appropriate value [29]. Although their approach is interesting, it only provides a qualitative insight. Moreover, the other parameter d, (as shown in figure 11, $d + a$ is the distance between the

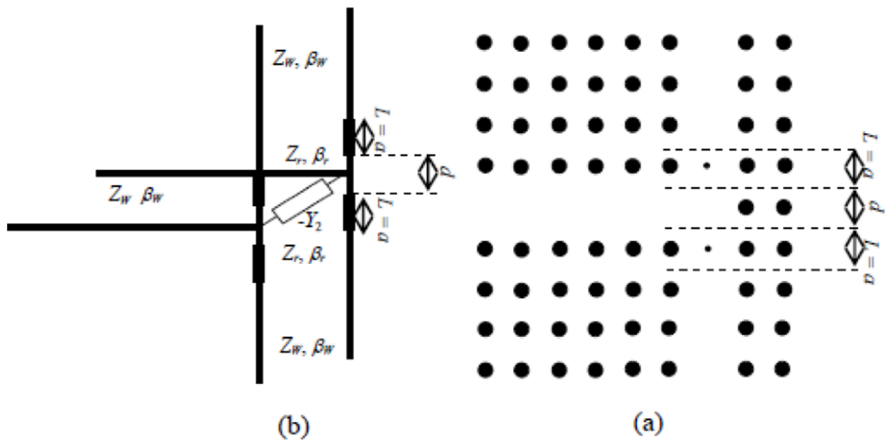

Figure 11. (a) A T-junction with two rods inserted at the output ports as matching stages. (b) The proposed transmission line model in which the stub and cascade models are applied for modeling T-junction and matching stages, respectively.

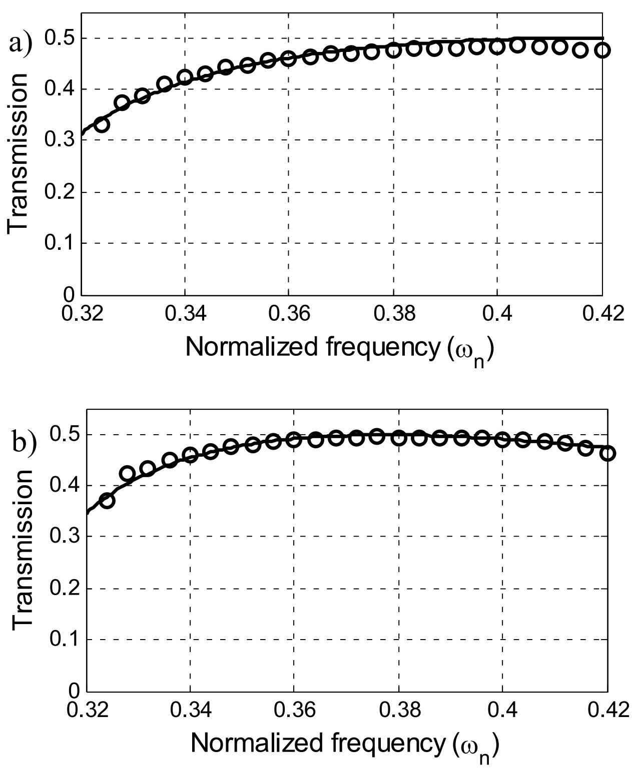

Figure 12. Transmission spectra of T-junction shown in figure 11 are obtained by the circuit model (solid line) and FDTD (circles). The results are illustrated for (a) $d = a$, (b) $d = 1.3a$.

center of the small rods) was not adjusted in their work, and it was simply assumed to be equal to a [29]. The transmission of the structure by these assumptions ($d = a$ and $r = 0.07a$) is plotted in figure 12(a), obtained by the proposed circuit model (solid line) and FDTD (circles).

Using the proposed circuit model, it is found that choosing $d = 1.3a$ can further improve the transmission of T-junction, as illustrated in figure 12(b). It is seen that the transmission remains more than 48% for $\omega_n = 0.352$–0.412 and is almost complete at $\omega_n = 0.378$. Although this simple design leads to relatively high transmission in a large bandwidth, better performances can be obtained by numerical optimization [30].

6. Conclusion

A circuit model which can be used for the efficient analysis of many PhC devices has been developed. Particularly, as some important examples, coupled waveguide-cavity systems exhibiting Fano resonance, sharp bends and T-junctions have been investigated. It was shown that the proposed model can predict the behavior of these structures. Moreover, thanks for the insight given by the circuit model, simple approaches have been proposed to reduce the reflection loss of sharp bends and T-junctions.

The concept presented in this paper can be applied to 3D PhC slabs by applying effective index method [31]. In this method the 3D structure is approximated with a 2D model in which the refractive index of the background dielectric material is replaced by the effective index of the fundamental guided mode of the 3D structures [31].

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