Characteristics of electromagnetic wave propagation in a segmented photonic waveguide

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In this study, frequencies of electromagnetic wave propagation in a four-segmented waveguide are obtained theoretically. There is a tight bonding in the transition of the photonic waveguide segments and thus it is assumed that these segments include no discontinuities. Effects of magnetic material properties on the electromagnetic wave propagation frequencies are investigated. Electromagnetic wave propagation frequencies are obtained with Maxwell equations. Moreover, reflection and transmission energy coefficients that occur with the change of material properties have also been investigated. Changing the material properties of the segmented photonic waveguide, amplification and damping events can be observed to occur.

(Received February 3, 2020; accepted October 22, 2020)

Keywords: Electromagnetic wave propagation, Multisegmented wires, Photonic waveguides, Maxwell equations

1. Introduction

Due to the fast developments in the areas of optics and electromagnetics, requirement of photonic structures increases more and more [1-5]. In recent years, phononic structures also have an important place since there are many studies on vibration and acoustics [22-25]. As is well known, the design methodologies of both phononic and photonic structures are based on electromagnetics and acoustic wave equations. Accordingly, in order to investigate the electromagnetic wave propagation behavior of the structures, the Maxwell equations must be solved [6-10].

To date, many applications of electromagnetic theory have been studied by various researchers [11-12]. These works have focused on switching systems. In [13], electromagnetic wave propagation frequencies of a specific structure that has non-uniform material properties have been examined.

To understand wave propagation properties, it is necessary to know the characteristics of reflection and transmission. The reflection and conduction characteristic that emerged as a result of electromagnetic wave propagation was examined in detail in [14-17].

In a planar lightwave circuit, the optical wave guiding can be designed to divide into two or more ways; conversely, more than one wave can be made to combine the guides. Several different techniques have been developed, including the photonic-crystalline structures. Thus, in the studies of [18-21], microwave and waveguide topics were investigated. Using classical dynamics in [22-24], the wave propagation was examined in phononic structures. In this context, using piezomagnetic element, wave propagation characteristic is investigated by one dimensional (1D) transfer matrix model [22]. Using photonic crystals, the crystal filter is placed at different angles; we can get the image on the screen. As Fig. 1, depending on the horizontal and vertical position of the filter, the image can be obtained on the screen.

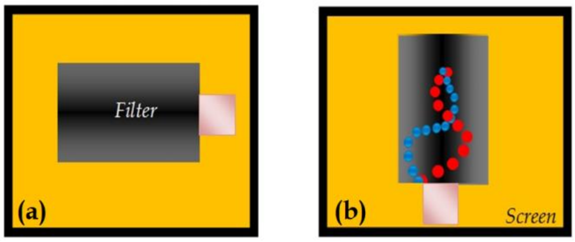

Fig. 1. (a) Horizontal placed filter, (b) Vertical placed filter screen view (color online)

Inner structure of this crystal filter is shown in Fig. 2. Basically, the inner structure of the crystal Filter consists of 4 main parts. These are Polarizing Filter, Glass Substrate, Transparent Electrodes, Liquid Crystals. These are symmetrically laminated together. In the core of the structure, liquid crystals segment (layer) is located.

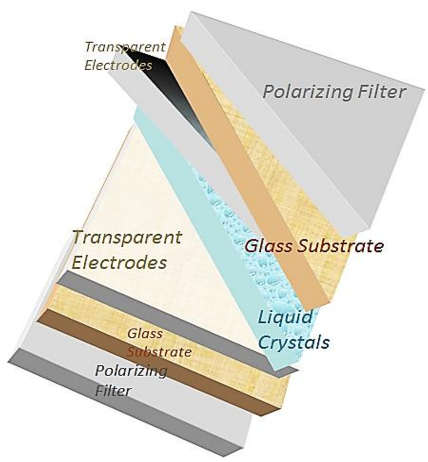

Fig. 2. The structure of photonic crystal filter (color online)

By using Transfer Matrix Method, the wave transmission between each layer in a phononic structure is examined in detail in the transmission [23]. In the mentioned study, the wave propagation of the structure designed as phononic crystal of laminated aluminum layers and aluminum-graded structures are examined. The characteristics of wave entered into the structure with the angle and the progress of the structure has been investigated [24].

The dielectric properties (μ, ε) of this created metamaterial structure are examined in detail [25-26] and the wave propagation behavior of this structure is examined [27-28]. Additionally, electromagnetic wave propagation behaviors of photonic band gap structures with sinusoidal dielectric permittivity are investigated [29]. Additionally, transmission and reflection characteristics of waveguides are studied [30-31].

In this article, electromagnetic wave propagation of segmented structures will be examined. It has been studied on different structures (wires) connected to each other. The issue that will focus on this subject is the change of material properties and the frequency of wave propagation frequencies. In addition, the reflection and transmission coefficients will be examined, as well as a detailed examination of the transmission of the wave.

2. Theoretical analysis

Proposed bisegmented, conductive waveguide configuration is illustrated in Fig. 3. The electromagnetic wave propagation characteristic obtained in this segmented waveguide is given in Fig. 3. It should be noted that, this EM wave created by an EM force effect, is also fed from an electromagnetic source and propagates as its properties are shown in Fig. 3. The two segments of the wire (waveguide) are different in terms of material characteristics, μ and ϵ. The electromagnetic wave travels from the first segment of the wire to the second segment through each segment, lossless. The place where the loss occurred is at the junction of the two segments.

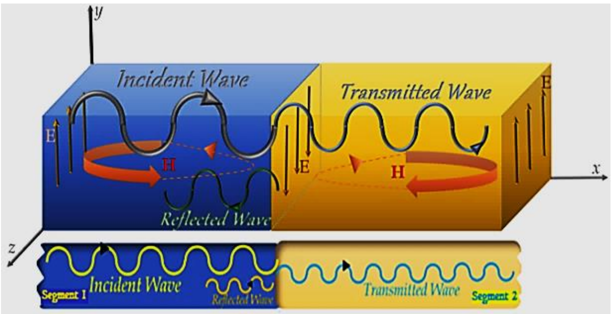

Fig. 3. Wave propagation of the segmented waveguide (color online)

Second derivation express is applied to Helmholtz equation. In a source free, linear isotropic and homogenous region, Maxwell's equations are [2]:

$$\nabla x\vec{E} = -j\omega\mu\vec{H} \tag{1a}$$

$$\nabla x\vec{H} = -j\omega\epsilon\vec{E} \tag{1b}$$

where, μ is permeability, ϵ is permittivity, E is electrical field (axis *y*) and H is magnetic field (axis *x*) (axis *z*). Herein, the traveling wave under the effect of an electromagnetic force is analyzed and in this context the particle model is used. Therefore, the 3-dimensional wave equation given as Equ. 2 is obtained by using Maxwell equations given in Equ. (1a) and Equ. (1b). *U(H)* is the wave propagation field of the wire.

$$\frac{\partial^2 H_x}{\partial x^2} + \frac{\partial^2 H_y}{\partial y^2} + \frac{\partial^2 H_z}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 H_x}{\partial t^2} = 0 \tag{2}$$

$$u_1(x,t) = U_1 e^{i(\omega t - k_1 x)} + U_1 e^{i(\omega t + k_1 x)} \tag{3a}$$

$$u_2(x,t) = U_2 e^{i(\omega t - k_2 x)} \tag{3b}$$

where, $U_{1\text{-}in}$ is incident wave of first wire, $U_{1\text{-}rf}$ is reflected wave of first wire and $U_{2\text{-}tr}$ is transmitted wave of second wire. k_1 and k_2 are wave numbers in the first and second wire, respectively. ω shows the frequency of wave propagation. One dimensional wave propagation is:

$$\frac{\partial^2 H_x}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 H_x}{\partial t^2} = 0 \tag{4}$$

is obtained.

The equations of wave propagation of the first and the second wires, respectively, are given in (5a) and (5b), which are connected to each other and consist of two parts. By using these equations, the frequencies of wave propagation can be obtained.

$$U_1 - \frac{\omega^2 \mu_1 \epsilon_1 U_1}{{k_1}^2} = 0 \tag{5a}$$

$$U_2 - \frac{\omega^2 \mu_2 \epsilon_2 U_2}{{k_2}^2} = 0 \tag{5b}$$

The first and second wire differential equations are obtained. Where, (5a) and (5b) refers to equation of the first wire and equation of the second wire, respectively. In addition, the U_1 is wave of first wire and U_2 is wave of second wire.

$$k_{n+1} = k_n \sqrt{\frac{\mu_{n+1}\epsilon_{n+1}}{\mu_n \epsilon_n}} \tag{6}$$

To solve the Equ. (5a) and Equ. (5b), the ω values are obtained as the frequency parameters. Additionally *k*, wave numbers are solved by using Equ. (6).

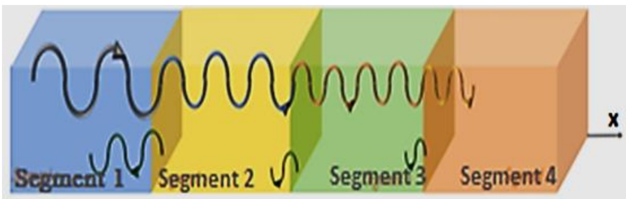

Fig. 4. Wave propagation of the waveguide (color online)

In Equ.s (7-8b), R and T indicate reflected and transmitted wave energies, respectively. If the material properties of the first and second segments (μ_n, ϵ_n) of the segmented wire are equal to each other, as the Equ.s (7-8b) suggests, reflection (R) will not be observed and the wave would be completely transmit.

$$R = \left(\frac{k_n - k_{n+1}}{k_n + k_{n+1}}\right)^2 \tag{7}$$

$$R + T = 1 \tag{8a}$$

$$R = \frac{4k_n k_{n+1}}{(k_n + k_{n+1})^2} \tag{8b}$$

3. Results and discussions

Behavior of the traveling wave depending on electromagnetic wave number k, is shown in Fig. 5.

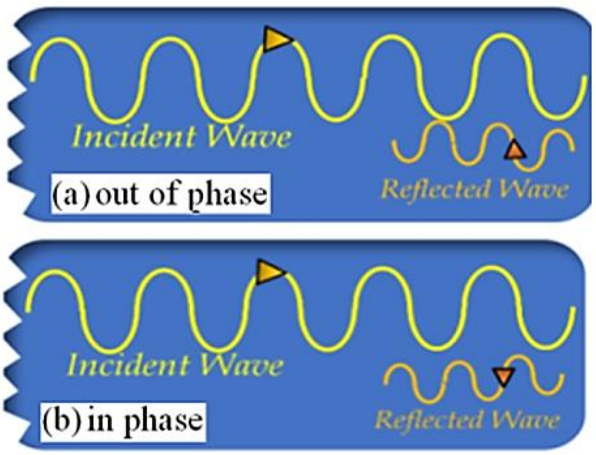

Fig. 5. Wave propagation type (a) $k_2 > k_1$ - out of phase, (b) $k_1 > k_2$ - in phase (color online)

In Fig. 5, condition a shows that $k_{n+1} > k_n$ incident wave and reflected wave are in phase, whereas condition b shows that $k_n > k_{n+1}$ incident wave and reflected wave are out of phase (Fig. 5).

Table 1.Segment properties of the waveguide (color online)

Case No	S1: Segment 1 S2: Segment 2		S2 – S3	S3 – S4
	μ_1,ϵ_1	μ_2,ϵ_2	μ_3,ϵ_3	μ_4,ϵ_4
1	1,1	2,3	4,5	6,7
2	1,1	1,1	1,1	1,1
3	1,1	2,2	1,1	2,2
4	4,4	3,3	2,2	1,1
5	1,1	4,4	2,2	3,3
6	1,1	4,4	9,9	16,16
7	1,1	0.5,0.5	0.33,0.33	0.25,0.25

The frequency of ω_1, Segment 1, ω_2, ω_3 and ω_4 show the frequencies of the second, third and fourth segments respectively. For every different seven cases of material properties, the four-segment structure is examined as can be seen in Table 1.

According to all seven different cases given in Table 1, frequency values and reflection and transmission coefficients for all four segments segmented wire are examined in Fig. 6 – Fig.19. In Case 1, material properties (ε, μ) of the four-segmented wire continuously increase whereas in Case 7, material properties of the four-segmented wire continuously increase. In Cases 2 and 5, $k_{n+1} > k_n$ incident wave and reflected wave are in the form of out of phase (Fig. 5).

The reflection coefficient of the wire that has homogeneous material properties is given in Case 2 and is obtained as 0, whereas transmission coefficient is obtained as 1. As a result, it should be noted that, every wave in this homogeneous wire is transmitted.

The reflection and transmission coefficients are given in Fig. 7 and Fig. 18 for Case 1 and Case 7, respectively. Where, T_{ba} indicates the transmission coefficient between wire segments of a and b. R_m indicates the wave reflection coefficient of m.th segment. In this study, it is assumed that each segment is connected to each other with perfect bonding. As a result, while the material property parameters (ε, μ) in each segment increase, the wave frequency values decrease.

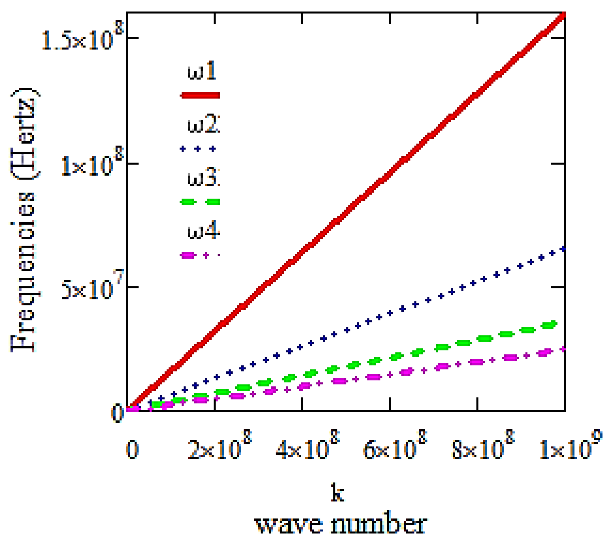

Fig. 6. EM wave propagation frequencies of Case 1 (color online)

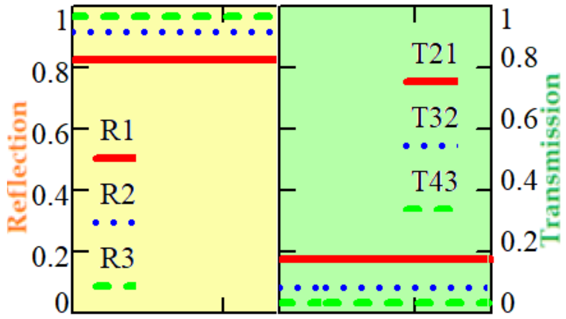

Fig. 7. EM wave propagation reflection and transmission coefficients of Case 1 (color online)

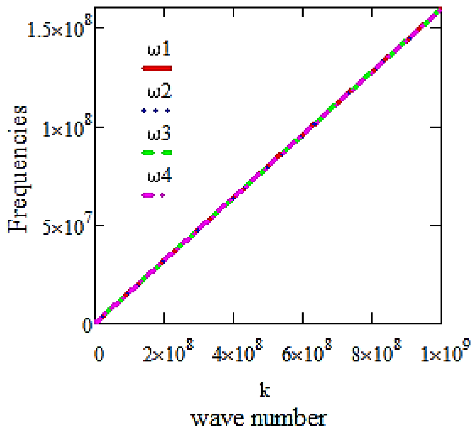

Fig. 8. EM wave propagation frequencies of Case 2 (color online)

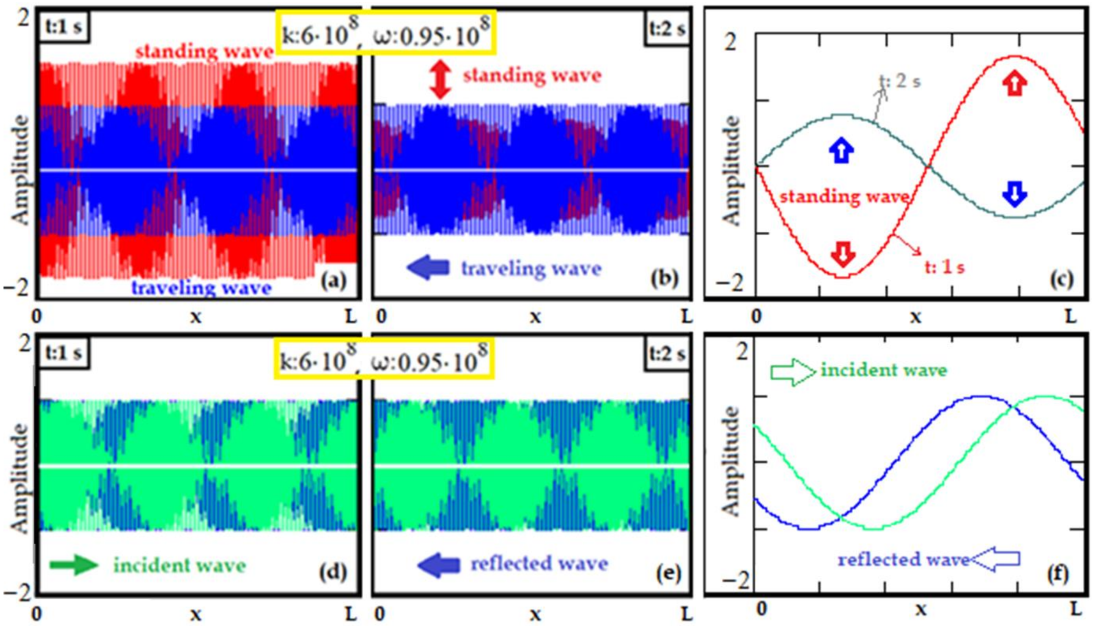

Fig. 9. Wave envelope profile in each segment of Case 2, (a) standing wave and traveling wave for t:1 s, (b) standing wave and traveling wave for t:2 s, (c) sinusoidal traveling wave form for t:1 s, (d) incident wave, (e) reflected wave and (f) sinusoidal standing wave form for t:1 s (color online)

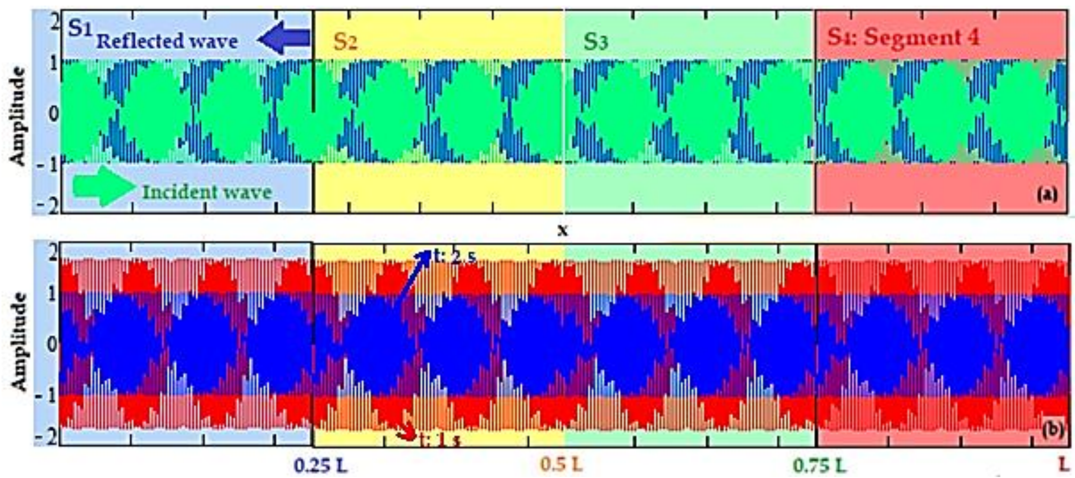

Fig. 10. Wave envelope profile in each segment, (a) traveling wave propagation characteristics for t: 1 s, (b) standing wave propagation characteristics for t:1 s and t: 2 s of Case 2 (color online)

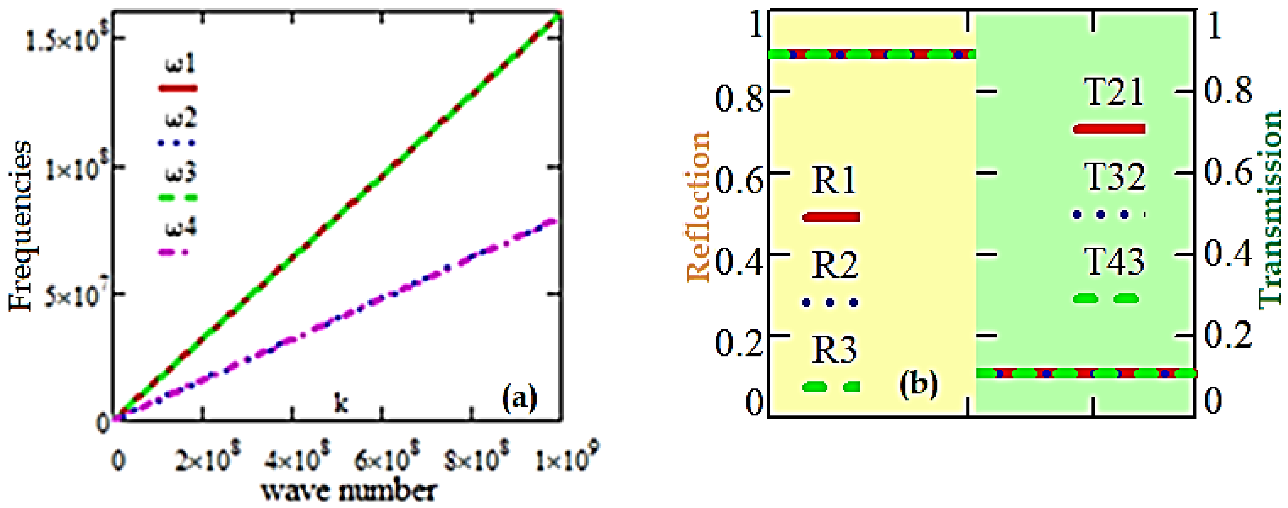

Fig. 11. a) EM wave propagation frequencies of Case 3, (b) reflection and transmission coefficients of Case 3 (color online)

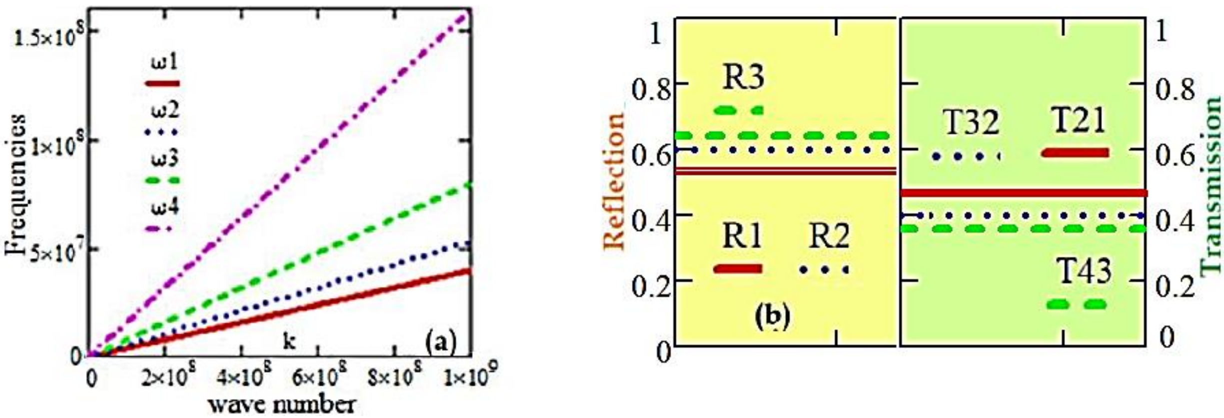

Fig. 12. (a) EM wave propagation frequencies of Case 4, (b) reflection and transmission coefficients of Case 4 (color online)

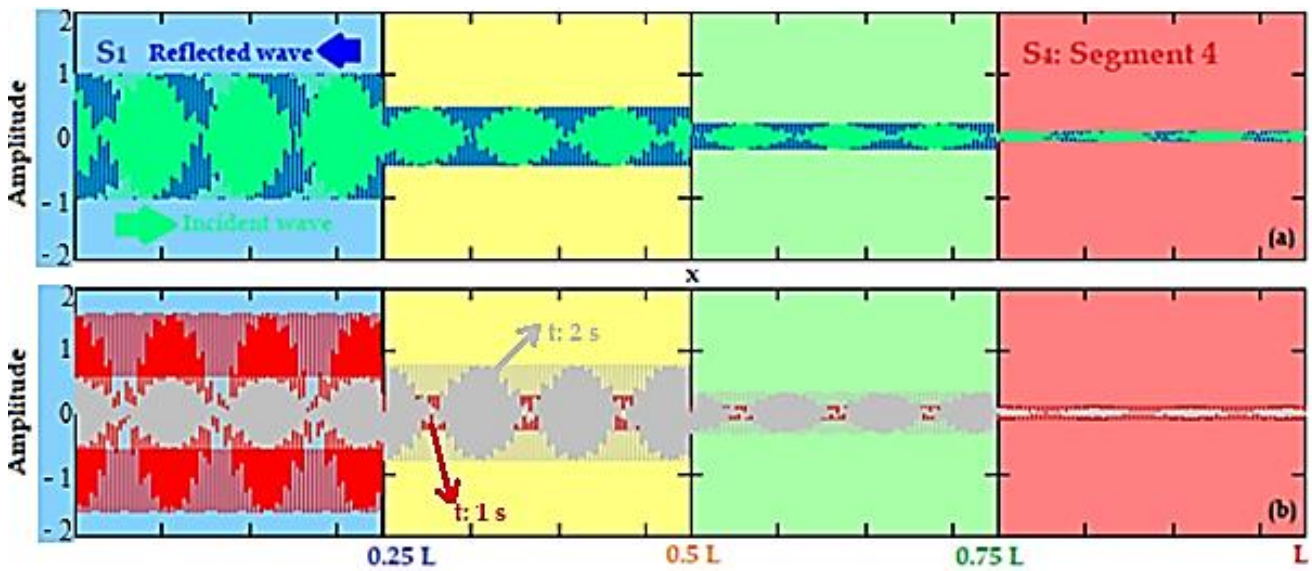

Fig. 13. Wave envelope profiles for each segment, (a) traveling wave propagation characteristics for t: 1 s, (b) standing wave propagation characteristics of Case 4 for t:1 s and t: 2 s (color online)

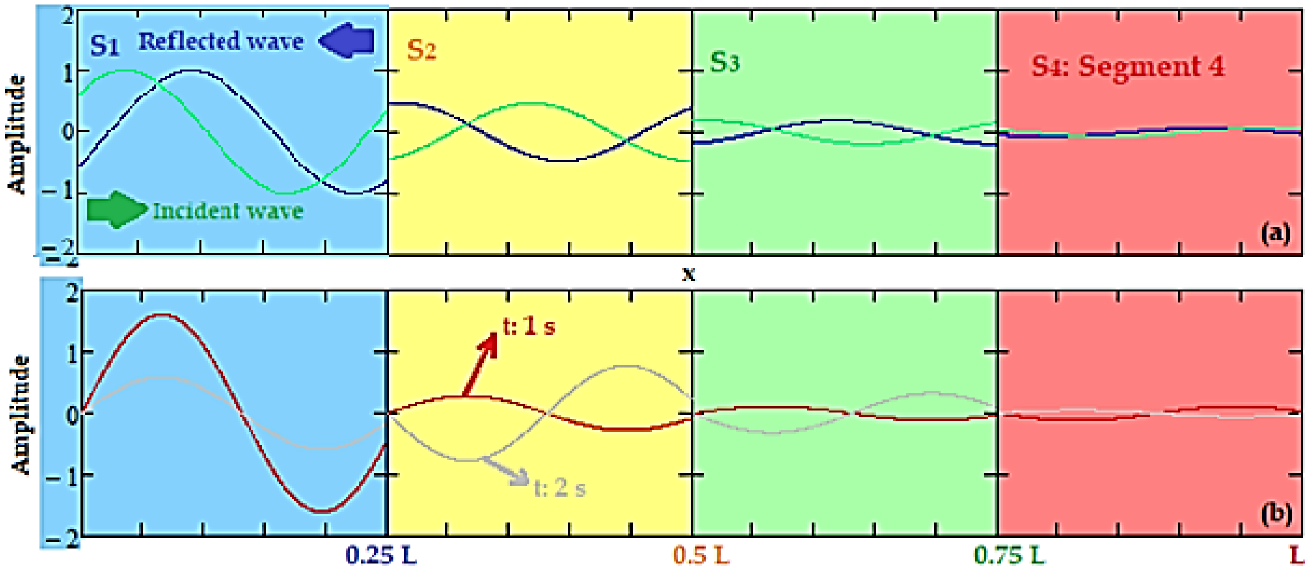

Fig. 14. Wave propagation of the sine wave along each segment, (a) sinusoidal traveling wave form propagation characteristics for t: 1 s, (b) sinusoidal standing wave form propagation characteristics of Case 4 for t:1 s and t: 2 s (color online)

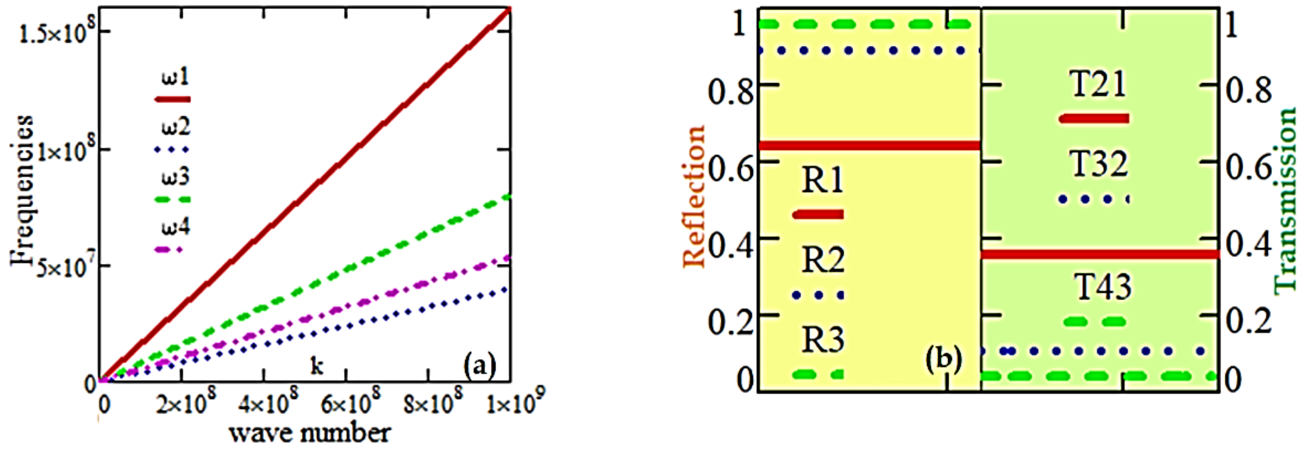

Fig. 15. (a) EM wave propagation frequencies of Case 5, (b) reflection and transmission coefficients of Case 5 (color online)

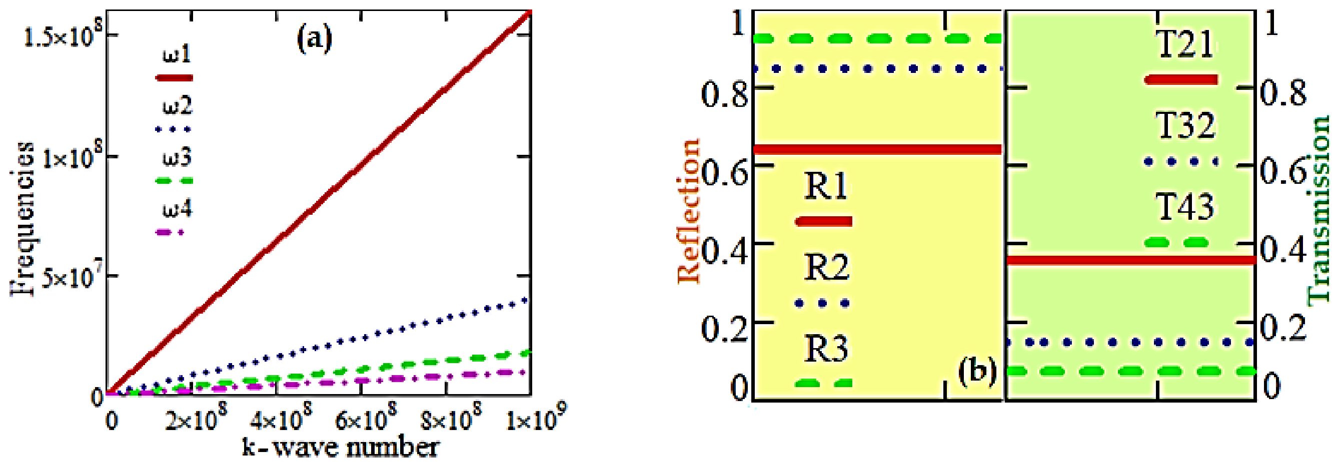

Fig. 16. (a) EM wave propagation frequencies of Case 6, (b) reflection and transmission coefficients of Case 6 (color online)

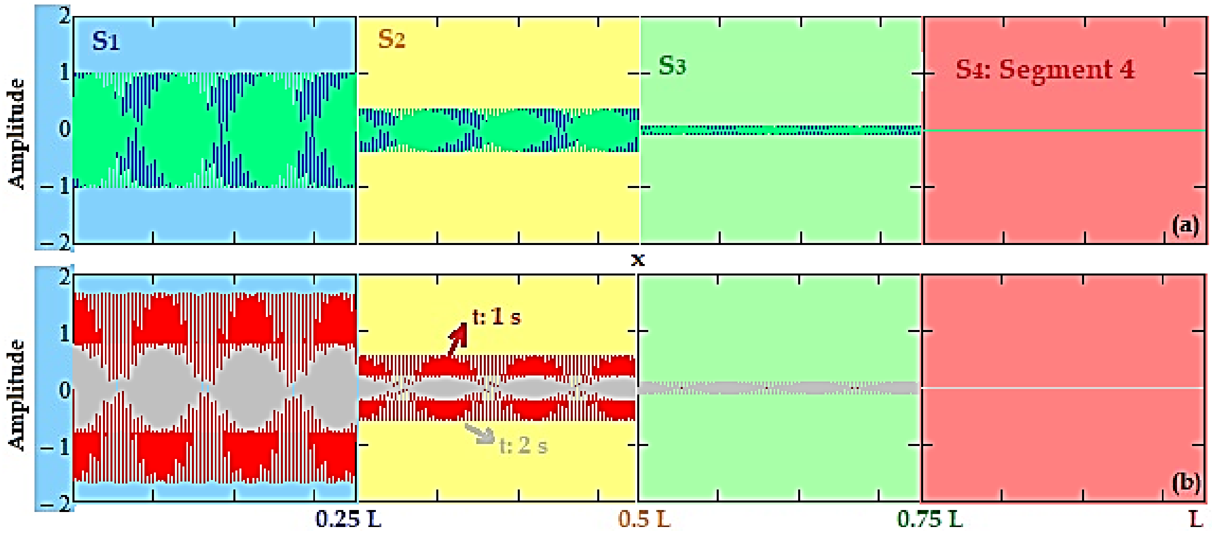

Fig. 17. Wave envelope profiles for each segment, (a) traveling wave propagation characteristics for t: 1 s, (b) standing wave propagation characteristics of Case 6 for t:1 s and t: 2 s (color online)

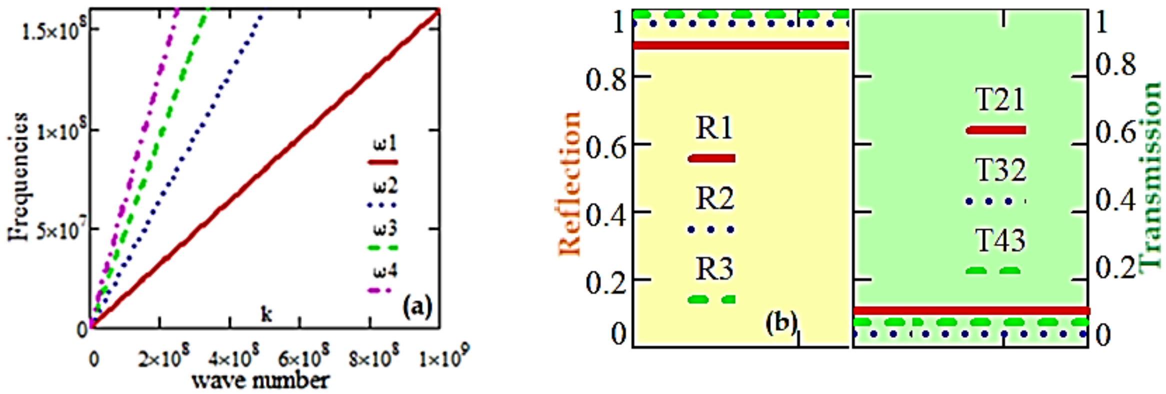

Fig. 18. (a) EM wave propagation frequencies of Case 7, (b) reflection and transmission coefficients of Case 7 (color online)

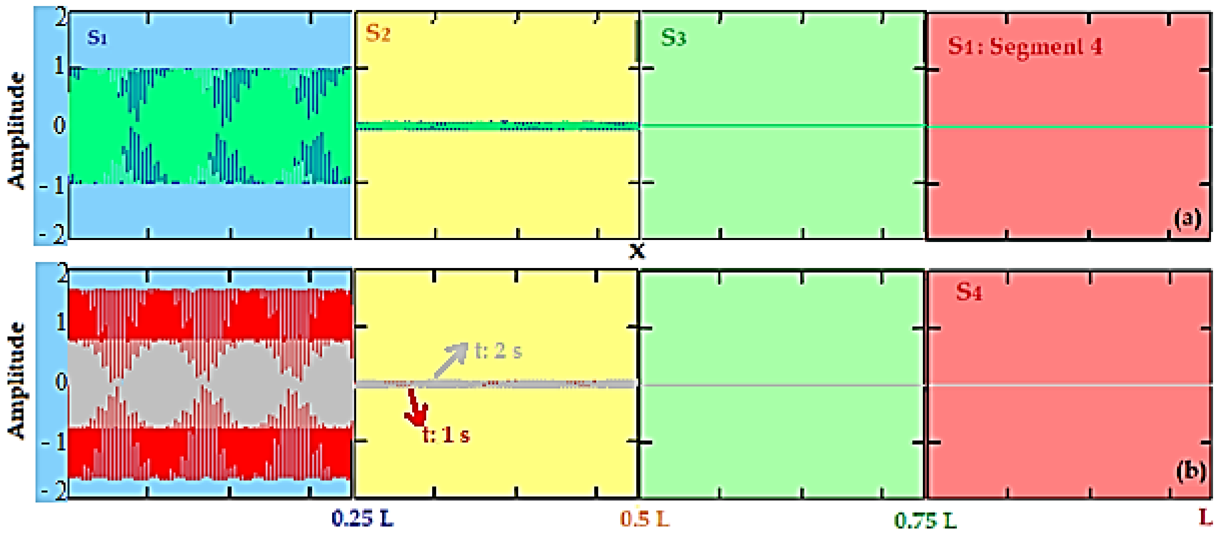

Fig. 19. Wave envelope profiles for each segment, (a) traveling wave propagation characteristics for t: 1 s, (b) standing wave propagation characteristics of Case 7 for t:1 s and t: 2 s (color online)

As can be seen in Fig.s 9 - 10, Fig.s 13 – 14, Fig. 17 and Fig. 19, standing-wave and traveling-wave characteristics are examined. Accordingly, different wave propagation characteristics for each segment of the wire are obtained. As shown in Fig.s 9 – 10, when each segments of the wire has the same material properties as given in Case 2, the reflection coefficients are obtained as zero. As can be seen in Fig.s 13 - 14, when the traveling-wave is examined from Segment 1 to Segment 4, a decrease in the amplitude level of the traveling wave occurs. In addition, for Case 4, the values of the reflection and the transmission coefficients which are obtained to be very close to each other are also obtained around 0.5. As shown in Figs. 13 and 17, the wave propagation behavior in the first two segments of the wire is very similar to each other, despite the material characteristics of all the wire segments have different material characteristics. As can be seen in Fig.s 13 and 19, the wave propagation behaviors for the last two segments of the wire are very similar to each other. It should be noted that, the obtained wave amplitude values from Segment 1 to Segment 4 decrease with a ratio of 1/1000.

All the obtained figures related (k-ω) within this study are summarized in Fig. 20. As can be shown in Fig. 20, the wave frequency decreases while the material property parameters of the segmented wire increase when the material properties equal to 1, it is observed that the graph including the wave propagation frequencies was obtained have red colored linear line (45°). Additionally, in the upper region of the Fig. 20, material properties are obtained to be less than 1, whereas in the lower region of the Fig. 20 material properties are obtained to be greater than 1.

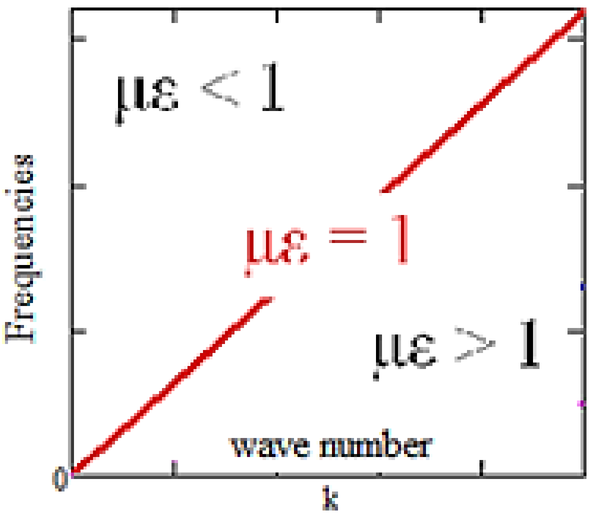

Fig. 20. EM wave propagation frequencies of all Cases (color online)

4. Conclusions

In this paper, effects of segmented wire properties on electromagnetic wave propagation frequencies and wave characteristics were investigated. For this purpose, the frequency values of electromagnetic wave propagation occurring in a conductive wire whose segmented parts properties are obtained. By changing the material properties on both wires, wave propagation behavior in segmented-wire is examined. As a result of the study, the frequency of wave can be adjusted by combining wires of different characteristics. In addition, the electromagnetic wave propagation behaviors (the reflection and the transmission) have been examined in a detailed way in different cases. As a future research, this analysis can also be performed for two-dimensional photonic structures.

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