Progress In Electromagnetics Research C, Vol. 141, 143-150, 2024
PIER C

(Received 11 November 2023, Accepted 26 January 2024, Scheduled 14 February 2024)

Tunable Filters Based on Fano Resonance Using Asymmetric Moving Resonators in a Single Loop System

Mimoun El-Aouni[1], Youssef Ben-Ali[2,*], Ilyass El Kadmiri[3], Younes Errouas[1], Abdelaziz Ouariach[1], and Driss Bria[1]

[1]*Laboratory of Materials, Waves, Energy and Environment, Team of Waves, Acoustics, Photonics and Materials Mohamed I University, Oujda, Morocco*
[2]*Engineering Sciences Laboratory (LSI), Multidisciplinary Faculty of Taza, Sidi Mohamed Ben Abdellah University B.P. 1223, Taza Gare, Morocco*
[3]*Laboratory of Computer Science and Interdisciplinary Physics, ENSF, Sidi Mohamed Ben Abdellah University, Fez, Morocco*

ABSTRACT: We report a novel characteristic of the phenomenon of Fano resonance obtained by the interaction of incident electromagnetic waves and waveguides system formed of loop and resonators. The Green Function Method (GFM) is employed to calculate the transmittance of the incoming electromagnetic waves. Our proposed system achieve a selecting and filtering device either by total transmission or by total reflection with a very high performance. The proposed structure contains four segments of the same lengths, and asymmetric resonators (N and N' resonators) are moving in the structure. Through parameters optimization, we show that the system creates Fano resonances, which are sensitive to the variations of the segment lengths, the resonator lengths, the positions of the resonators, and the physical properties of the system components. Then, the proposed system is able to filter at least two resonance modes with different frequencies. This system has potential applications in the field of microwave communication antennas.

1. INTRODUCTION

In the last decades, enormous research has been conducted in the development of inexpensive, accurate, reliable electromagnetic and microwave filters capable of filtering and selecting one or several frequencies. A filter (selecting waves system) is a device that can transmit or reject a portion of the electromagnetic waves. Numerous filters based on waveguide systems have been proposed and manufactured to control and select several frequencies. Photonic waveguides system can be considered as one of the most recent photonic technologies because of its extraordinary photonic properties for a set of applications [1–7]. The photonic waveguide structures have attracted important attention by the scientific community due to their ability to guide and confine the electromagnetic waves [8]. Megahertz (MHz) radiation lying in the frequencies range from 0 to 1000 MHz has gathered significant importance thanks to their high transmission, low energy, high signal-to-noise ratio (SNR), and wide bandwidth. This area of electromagnetic waves has a wide variety of applications such as MHz imaging, MHz filtering, space science, security screening, communication, spectroscopy, ultrafast computing, medical sciences, and environmental monitoring [9–12].

Recently, one-dimensional (1D) photonic periodic waveguides system filters based on the resonators in the megahertz band have been widely concerned by different authors [13, 14]. Ben-Ali et al. studied the transmission spectra of a one-dimensional photonic periodic star waveguides system with either left-handed materials or right-handed materials for applications in reflector and passband filters [15, 16]. Errouas et al. also proposed a new system based on electromagnetic star waveguides, which are able to select and filter one or two incoming electromagnetic waves [17]. On the other hand, El-Aouni et al. suggested the idea of a narrow tunable filter based on the interaction of the incoming electromagnetic wave and one-dimensional defectives photonic serial loops system [18].

In this work, we propose a new typical 1D waveguides system formed of segments and resonators. This structure contains four segments of the same lengths, and asymmetric resonators are moving in the system. Based on the scientific literature, such type of waveguides non-periodical structure based on the loop and resonators (if we consider either the resonator or the loop) has the capacity to create Fano resonances in the transmission spectrum [5]. These Fano resonances can be used to realize devices such as electromagnetic switches, lasers, sensors, ultrafast switches, and slow-electromagnetic wave's devices [19–22]. A Fano resonance is a type of resonant scattering phenomenon that gives rise to an asymmetric line-shape (asymmetric peak). Interference between a background and a resonant scattering process produces the asymmetric line-shape [23–27]. This work demonstrates, on the one hand, the existence of Fano resonances, which are characterized by a very high transmission rate and an important quality factor Q, and on the other hand, the results will show that other resonance modes are characterized by transmission zero, which can be used as a total reflection filter. Based on these results, we can use the proposed system as filtering in the telecommunication application

* Corresponding author: Youssef Ben-Ali (youssefplanck@gmail.com).

doi:10.2528/PIERC23111104

Published by THE ELECTROMAGNETIC ACADEMY

field in the MHz areas, such as antennas, radio frequency and radars [28–31].

2. MODEL AND FORMALISM

In this paragraph, we develop the Green function method (GFM) to study the electromagnetic waves propagation in electromagnetic waveguides system. In this situation, we consider that our structure is constituted by a loop characterized by the lengths d_1, d_2, d_5, d_6, and N and N' resonators of lengths respectively d_3 and d_4. We can define this theory as [32]:

$$g(DD) = G(DD) - G(DM)G^{-1}(MM)G(MD) + G(DM)G^{-1}(MM)g(MM)G^{-1}(MM)G(MD) \quad (1)$$

where D and M are respectively the hole space and interface space in the system. G represents a block-diagonal matrix where each sub-block G_k corresponds to the global Green's function of substructure k. Based on the knowledge of the elements of the matrix $g(MM)$ of g in the interface space M, we determine the elements of the matrix $g(DD)$ of the composite material.

The inverse of the Green function of the system composed by loops-resonators (see Fig. 1(b)) is written in the following form:

$$\overleftrightarrow{g}_{sys}^{-1}(M_m M_m) = \begin{pmatrix} -\frac{F_1C_1}{S_1}-\frac{F_2C_2}{S_2}-F_s & \frac{F_1}{S_1} & \frac{F_2}{S_2} & 0 \\ \frac{F_1}{S_1} & -\frac{F_2C_2}{S_2}-N\frac{F_3S_3}{C_3}-\frac{F_5C_5}{S_5} & 0 & \frac{F_5}{S_5} \\ \frac{F_2}{S_2} & 0 & -\frac{F_2C_2}{S_2}-N'\frac{F_4S_4}{C_4}-\frac{F_6C_6}{S_6} & \frac{F_6}{S_6} \\ 0 & \frac{F_5}{S_5} & \frac{F_6}{S_6} & -\frac{F_5S_5}{C_5}-\frac{F_6S_6}{C_6}-F_s \end{pmatrix} \quad (2)$$

$C_i = \text{Cosh}(\alpha_i d_i)$; $S_i = \text{Sinh}(\alpha_i d_i)$ and $\alpha_i = F_i = -j\frac{\omega}{c}\sqrt{\varepsilon_i}$ ($i = 1, 2, 3, 4, 5, 6$); F_s represents the inverse Green function of the semi-infinite segment (guide); c is the speed of electromagnetic waves (light) in vacuum; ε_i is the dielectric constant; ω represents the pulsation and $j = \sqrt{-1}$.

For the photonic waveguides structure situated between two semi-infinite guides (Fig. 1), the transmission rate T and reflection rate R are given respectively as:

$$T = |-2F_s g(e,s)|^2 \quad (3)$$

$$R = |-1-2F_s g(e,e)|^2 \quad (4)$$

where 'e' and 's' represent, respectively, the interface between the input semi-infinite guide and the structure, and the interface between the output semi-infinite guide and the structure.

3. RESULTS AND DISCUSSIONS

We will assume that the diameters of the various components of the system are very small compared to their lengths, which allows us to consider that electromagnetic waves propagate along a single dimension. Electromagnetic waves originating from a semi-infinite waveguide propagate in the medium (segment) characterized by the same physical properties as the semi-infinite waveguide. Wave scattering in the multi-interface structure, considering a composite material, involves propagation along different paths, giving rise to constructive and destructive interferences.

In this section, we analytically illustrate the propagation of electromagnetic waves through a photonic waveguides structure containing a loop and position-varied resonators. We define the reduced frequency Ω by: $\Omega = \frac{\omega D}{C}\sqrt{\mu_i \varepsilon_i}$ where, $D = d_1 + d_5$.

3.1. Symmetric Loop without Resonators

First, we consider the structure composed by symmetric loop characterized by lengths d_1 and d_2 (Fig. 1(a)). In Fig. 2, we present the variation of transmission rate as a function of the reduced frequency Ω, we can see that there exists one large resonance mode (low quality factor) with a maximum transmission peak around the reduced frequency $\Omega = 2.1$. This system can filter one frequency at $f = 152$ MHz when the length $d_1 = d_2 = 1$ m and $\varepsilon_1 = \varepsilon_2 = 2.3$. In the case when the loop is symmetric, the transmission rate cannot reach zero [33]. Indeed, the transmission rate does not fall below the value $T = 0.6$. In the following, we will introduce two resonators that move inside the system, and we will study their effect on the transmission rate.

3.2. Effect of the Two Resonators Displacement In the System

In the following paragraph, we present in Fig. 3 the variation position effect of the two resonators ($N = N' = 1$) of lengths d_3 and d_4 on the transmission spectrum. Note that when we change the segments lengths d_1 and d_2, the resonators move in the structure.

We consider $d_1 + d_5 = d_2 + d_6 = D$ and take three cases where the positions of resonators are well determined. In case (a) where the two resonators occupy the ends of the loop system ($d_1 = d_2 = D$ and $d_5 = d_6 = 0D$), we obtain a very narrow filtered resonance mode (high quality factor) with a total transmission ($T = 1$) around the reduced frequency $\Omega = 2.1$. For it, we can use this system in question for filtering one frequency around $f = 152$ MHz if the geometrical parameters are as follows $d_1 = d_2 = 1$ m, $d_3 = 0.54$ m, and $d_4 = 0.46$ m. This case (a) cannot be obtained when the propagation of electromagnetic waves is studied through the asymmetric or symmetric loop without resonators [33]. In case (b), we change the position of the two resonators in the following way: we put the resonator of length d_3 at a distance $d_1 = 0.9D$ and the resonator of length d_4 at a distance $d_2 = 0.9D$, and we obtain two resonances frequencies (Fig. 3(b)), namely $\Omega_1 = 1.75$ with low quality factor and $\Omega_2 = 2.2$ with high quality factor. Consequently, this system behaves as a filtering system

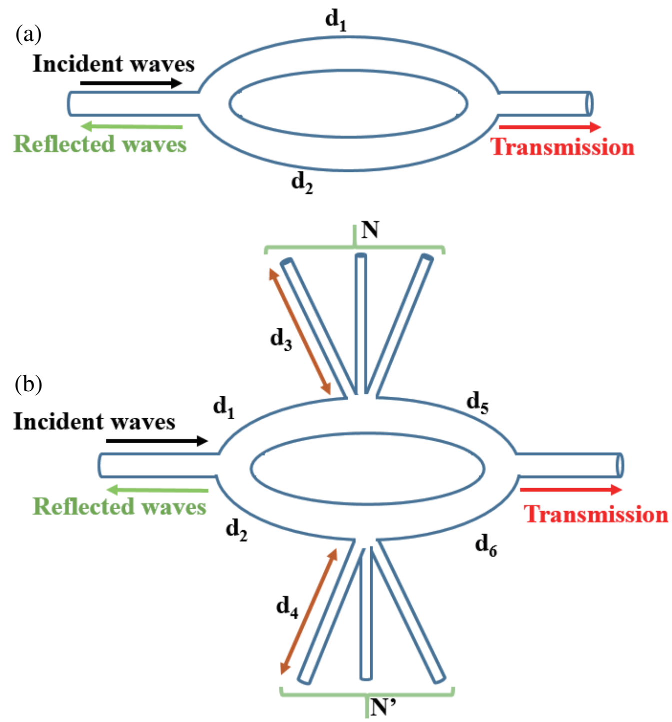

FIGURE 1. (a) Symmetric loop waveguides of length $d_1 = d_2$ without resonators situated between two semi-infinite media of the same nature. (b) Waveguides structure consists of four segments of the same lengths $d_1 = d_2 = d_5 = d_6$ and N and N' position-varying resonators of lengths d_3, d_4 and the relative permittivities $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_5 = \varepsilon_6 = 2.3$.

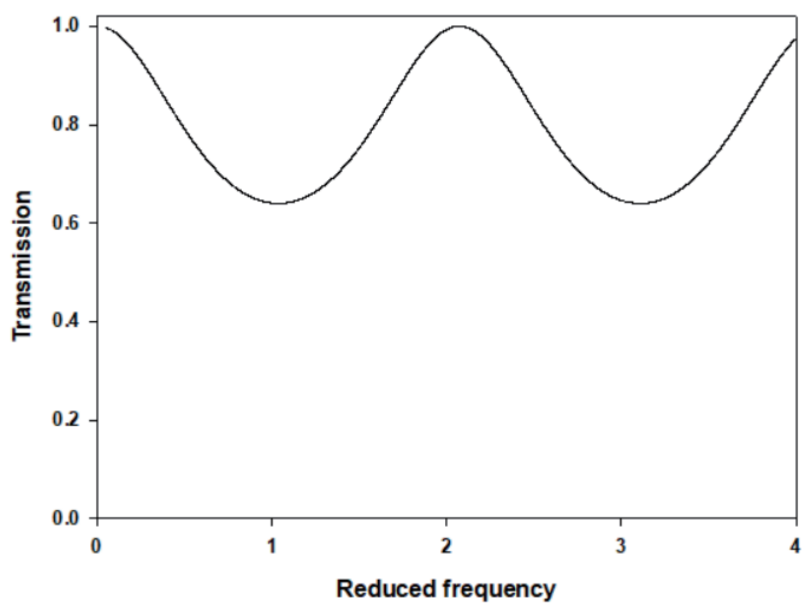

FIGURE 2. Transmission rate as a function of the reduced frequency Ω when the length $d_1 = d_2 = D$ and $\varepsilon_1 = \varepsilon_2 = 2.3$.

that can filter two frequencies of values $f_1 = 126.719\,\text{MHz}$ and $f_2 = 159.30\,\text{MHz}$ if the geometrical parameters are $d_1 = d_2 = 0.9\,\text{m}$, $d_3 = 0.54\,\text{m}$, $d_4 = 0.46\,\text{m}$, and $d_5 = d_6 = 0.1\,\text{m}$. In case (c), the two resonators situated at a distance of 0.5D from the input system. In this case, the system shows two total transmission rates (shape of Fano resonances) around the frequencies $f_1 = 90.5\,\text{MHz}$ and $f_2 = 210\,\text{MHz}$ and a transmission zero (total reflection) around $f = 152\,\text{MHz}$ when the geometrical parameters are $d_1 = d_2 = 0.5\,\text{m}$, $d_3 = 0.54\,\text{m}$, $d_4 = 0.46\,\text{m}$ and $d_5 = d_6 = 0.5\,\text{m}$.

3.3. The Position of The Resonator d_3

In the present paragraph, we take the resonance mode localized around Ω [1.98, −2.16] and investigate, in Fig. 4, the variation of the reduced frequency as a function of the position of the res-

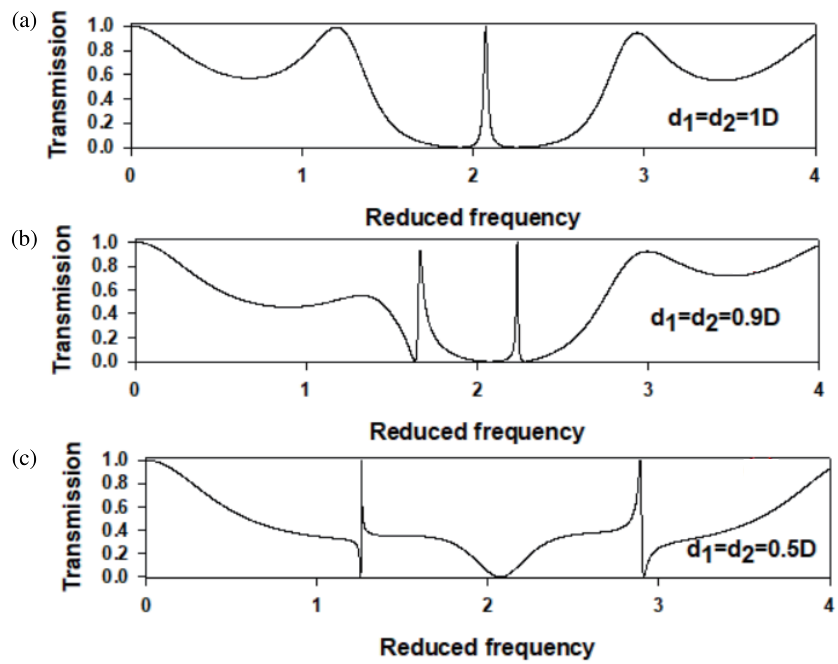

FIGURE 3. The effect of the position of the two resonators ($N = N' = 1$) of lengths $d_3 = 0.54D$, $d_4 = 0.46D$ (by changing the lengths d_1 and d_2) and $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_5 = \varepsilon_6 = 2.3$.

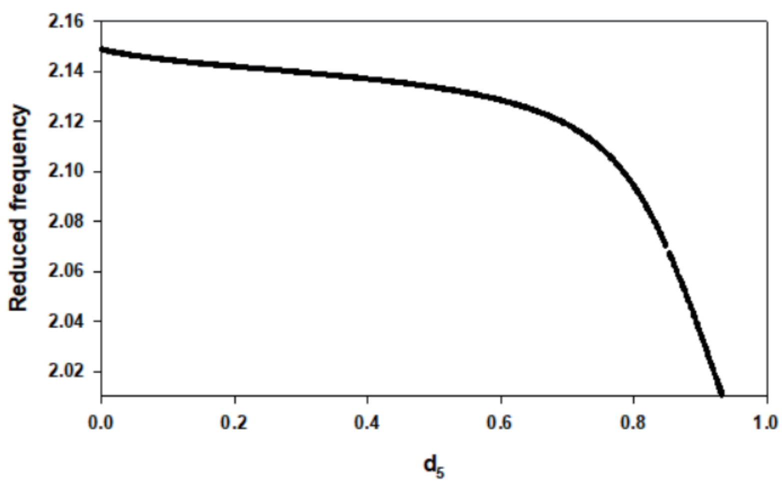

FIGURE 4. Variation of the reduced frequency Ω as a function of the length d_5 with $d_2 = 0.9D$, $d_6 = 0D$, $d_3 = 0.54D$, $d_4 = 0.46D$ and $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_5 = \varepsilon_6 = 2.3$.

onator of length d_3 by keeping the other parameters as follows $d_2 = D$, $d_6 = 0$, $d_3 = 0.54D$, and $d_4 = 0.46D$. It is noted that the change in the position of the resonator (d_3) depends on the variation of the segment of length d_1 and the variation of the segment of length d_5, as $d_1 + d_5 = 1D$. We conclude that the frequencies of resonance modes slightly decrease with the length d_5, and other modes keep the same value of the reduced frequency Ω for $d_5 = 0.95D$.

3.4. Effect of Opposite Displacement of the Two Resonators

The opposite displacement of the resonators (one resonator of length d_4 moves towards the system input and the other of length d_3 towards the output of the system) plays a very important role in the behavior of the resonance mode level. In this context, we study in Fig. 5 the behavior of the opposite displacement of the two resonators. According to Fig. 5, the resonance modes reach three transmission zeros. The transmission spectrum shows that the frequency of the two transmission zeros varied when the resonators move in the system, while a specific shape resonance mode around the reduced frequency $\Omega = 2.1$ was obtained which is independent of the displacement of the two resonators. The last mode of resonance can be induced by the interference of the incoming electromagnetic waves and the eigen modes of the loop-resonator with specific geometrical parameters. Therefore, we can use

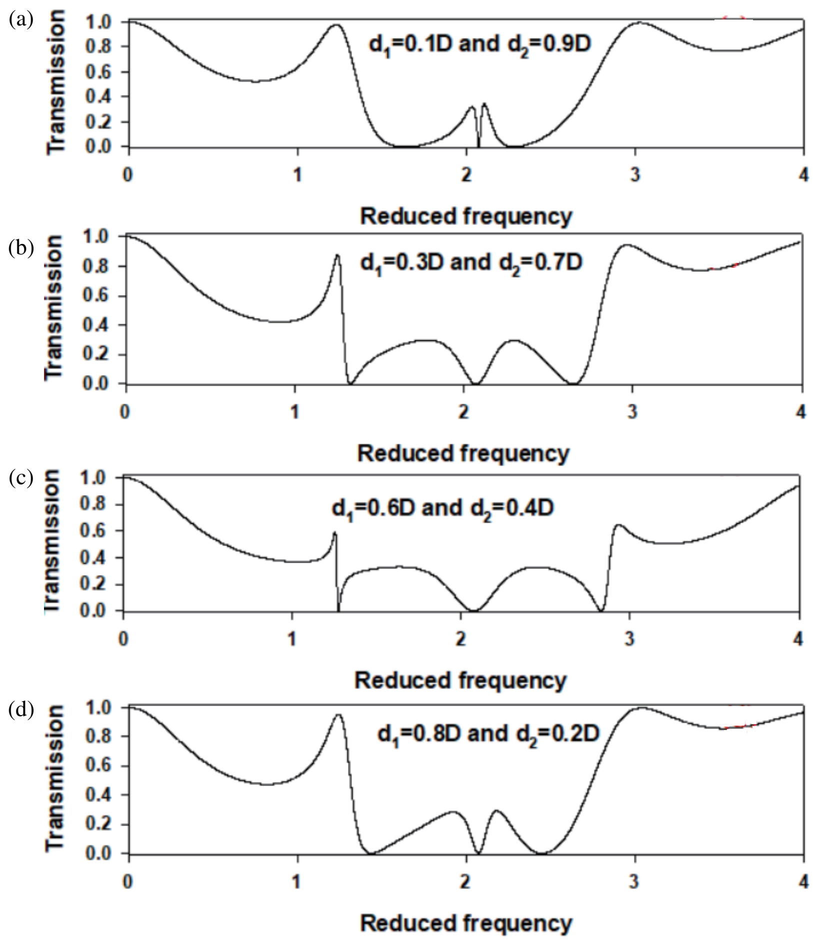

FIGURE 5. Transmission spectrum as a function of the reduced frequency Ω for the inverse displacement of the two resonators with $d_3 = 0.54D$, $d_4 = 0.46D$ and $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_5 = \varepsilon_6 = 2.3$. (a) $d_1 = 0.1D$ and $d_2 = 0.9D$. (b) $d_1 = 0.3D$ and $d_2 = 0.7D$. (c) $d_1 = 0.6D$ and $d_2 = 0.4D$. (d) $d_1 = 0.8D$ and $d_2 = 0.2D$.

this system as the total reflection filter that reflect three frequencies, namely $f_1 = 101.3754\,\text{MHz}$, $f_2 = 152.0631\,\text{MHz}$ and $f_3 = 188.2686\,\text{MHz}$ when the parameters $d_1 = 0.3\,\text{m}$, $d_2 = 0.7\,\text{m}$, $d_3 = 0.54\,\text{m}$, $d_4 = 0.46\,\text{m}$, $d_5 = 0.7\,\text{m}$ and $d_6 = 0.3\,\text{m}$.

3.5. Effect of Two Resonators Permittivities on the Resonant Modes

The variation permittivities of the media have a major effect on the electromagnetic response and can be used to improve the performance of the device. In this part, we fix the positions of two resonators and vary their permittivities in order to study the behavior of the resonance modes. Fig. 6(a) represents the transmission spectrum as a function of the reduced frequency Ω when the two resonators are located at distances $d_1 = d_2 = 0.9D$ from the entry point for different values of ε_3 and ε_4. Fig. 6(a) shows that the increase of the permittivities of both resonators with a step of 0.2 causes the decrease of the resonance modes frequencies. Fig. 6(b) shows the variation of the transmission rate versus the reduced frequency Ω when the permittivities of two resonators increase by a step of 0.2, with $d_1 = d_2 = 0.5D$. This last figure demonstrates that the zero of transmission moves to low frequencies when the resonators permittivities increase. The result may be exploited to build a selective filter with high performances.

3.6. Effect of N and N' Resonators on the Resonant Modes

In this section, we study the effect of inserting N resonators of length d_3 in the upper arm of the loop and N' resonators of length d_4 in the lower arm of the loop. We give the system the following parameters: $d_1 = d_2 = d_5 = d_6 = 0.5D$, $d_3 = 0.54D$ and $d_4 = 0.46D$. We show in Fig. 7(a) the transmission rate as a function of the reduced frequency Ω for $N = N' = 10$, in Fig. 7(b) the number of resonators as a function of the reduced frequency Ω and in Fig. 7(c) the variation of the quality factor Q as a function of the number of resonators. Fig. 7 shows the appearance of resonance modes with high transmission rates and different quality factors Q. The frequencies of these modes vary, and the quality factors Q increase as the number of resonators on each arm of the loop increases. In this case, we consider the multiple-resonators system to function as a multi-frequency filter.

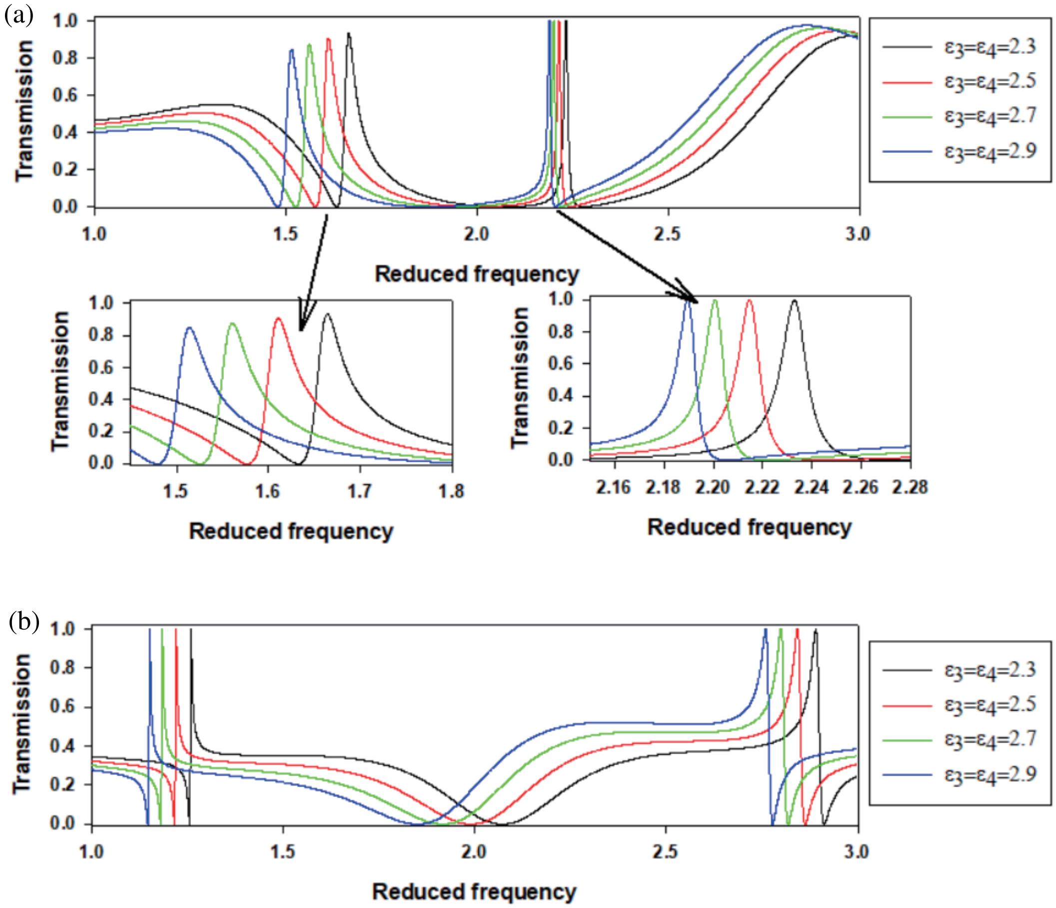

FIGURE 6. Transmission rate as a function of the reduced frequency Ω for different values of $\varepsilon_3 = \varepsilon_4$ and $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_6 = 2.3$. (a) The two resonators are located at distances $d_1 = d_2 = 0.9D$. (b) The two resonators are located at distances $d_1 = d_2 = 0.5D$.

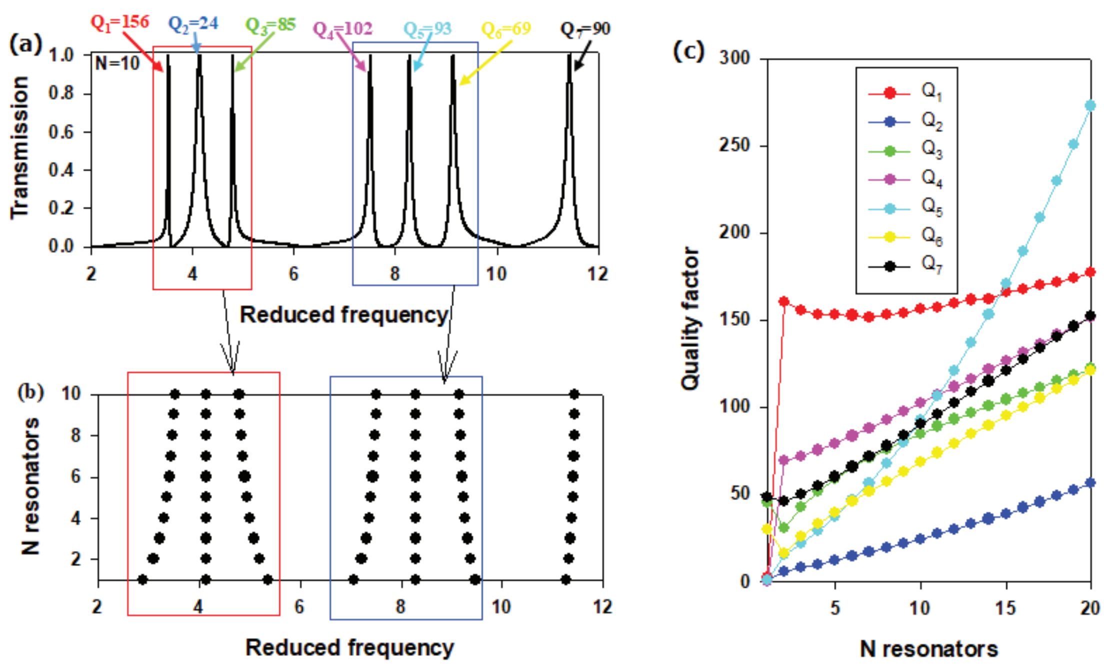

FIGURE 7. (a) The transmission rate as a function of the reduced frequency Ω for $N = N' = 10$. (b) The number of resonators as a function of the reduced frequency Ω. (c) The variation of the quality factor Q as a function of the number of resonators.

4. CONCLUSION

Following the Green function method, we have presented the phenomenon of Fano resonances and transmissions zero obtained by the interaction of the electromagnetic waves and one-dimensional waveguides system in order to achieve a selecting and filtering device either by total transmission or by total reflection with a very high performance. Our proposed system contains four segments of lengths d_1, d_2, d_5, d_6 asymmetric resonators (N and N' resonators) of lengths d_3 and d_4 that are moving in the system. Such a system creates Fano resonances and transmission zeros, which are sensitive to segments lengths, grafted resonators lengths, and the positions of resonators. Thus, by changing the physical and geometrical properties of the system components, the results show that the device is able to filter at least two resonances modes frequencies with maximum transmission rate and one transmission zero. We believe that this waveguides system based on the loop and resonators that move in the system is promising and has potential applications in the field of microwave communication antennas, radio frequency, and radars.

REFERENCES

[1] Liu, D., H. Xu, Y. Tan, Y. Shi, and D. Dai, "Silicon photonic filters," *Microwave and Optical Technology Letters*, Vol. 63, No. 9, 2252–2268, Sep. 2021.

[2] Khan, Y., A. U. Rehman, B. A. Batool, M. Noor, M. A. Butt, N. L. Kazanskiy, and S. N. Khonina, "Fabrication and investigation of spectral properties of a dielectric slab waveguide photonic crystal based fano-filter," *Crystals*, Vol. 12, No. 2, 226, 2022.

[3] Capmany, J., B. Ortega, and D. Pastor, "A tutorial on microwave photonic filters," *Journal of Lightwave Technology*, Vol. 24, No. 1, 201–229, Jan. 2006.

[4] Liu, Y., A. Choudhary, D. Marpaung, and B. J. Eggleton, "Integrated microwave photonic filters," *Advances in Optics and Photonics*, Vol. 12, No. 2, 485–555, Jun. 2020.

[5] El-Aouni, M., Y. Ben-Ali, I. El Kadmiri, and D. Bria, "Electromagnetically induced transparency and fano resonances base on coaxial photonic waveguide made up of asymmetric loop and resonators," *Key Engineering Materials*, Vol. 927, 178–188, 2022.

[6] Badri, S. H., S. SaeidNahaei, and J. S. Kim, "Hybrid plasmonic slot waveguide with a metallic grating for on-chip biosensing applications," *Applied Optics*, Vol. 60, No. 25, 7828–7833, Sep. 2021.

[7] Badri, S. H., H. Soofi, and S. SaeidNahaei, "Thermally reconfigurable extraordinary terahertz transmission using vanadium dioxide," *Journal of the Optical Society of America B*, Vol. 39, No. 6, 1614–1621, Jun. 2022.

[8] Monticone, F. and A. Alù, "Leaky-wave theory, techniques, and applications: From microwaves to visible frequencies," *Proceedings of the IEEE*, Vol. 103, No. 5, 793–821, May 2015.

[9] Woolard, D. L., R. Brown, M. Pepper, and M. Kemp, "Terahertz frequency sensing and imaging: A time of reckoning future applications," *Proceedings of the IEEE*, Vol. 93, No. 10, 1722–1743, Oct. 2005.

[10] Sirci, S., J. D. Martínez, J. Vague, and V. E. Boria, "Substrate integrated waveguide diplexer based on circular triplet combline filters," *IEEE Microwave and Wireless Components Letters*, Vol. 25, No. 7, 430–432, Jul. 2015.

[11] Wiart, J., *Radio-Frequency Human Exposure Assessment: From Deterministic to Stochastic Methods*, John Wiley & Sons, 2016.

[12] Ben-Ali, Y., Z. Tahri, F. Falyouni, and D. Bria, "Study about a filter using a resonator defect in a one-dimensional photonic comb containing a left-hand material," in *Proceedings of the 1st International Conference on Electronic Engineering and Renewable Energy*, 146–156, 2018.

[13] El-Aouni, M., Y. Ben-Ali, I. E. Kadmiri, and D. Bria, "One-dimensional photonic serial asymmetric loops structure containing three defects," in *Defect and Diffusion Forum*, Vol. 418, 25–37, 2022.

[14] Ben-Ali, Y., A. Ghadban, Z. Tahri, K. Ghoumid, and D. Bria, "Accordable filters by defect modes in single and double negative star waveguides grafted dedicated to electromagnetic communications applications," *Journal of Electromagnetic Waves and Applications*, Vol. 34, No. 4, 539–558, 2020.

[15] Ben-Ali, Y., I. E. Kadmiri, A. Ghadban, K. Ghoumid, A. Mazari, and D. Bria, "Two-channel demultiplexer based on 1D photonic star waveguides using defect resonators modes," *Progress In Electromagnetics Research B*, Vol. 93, 131–149, 2021.

[16] Ben-Ali, Y., I. E. Kadmiri, Z. Tahri, and D. Bria, "High quality factor microwave multichannel filter based on multi-defectives resonators inserted in periodic star waveguides structure," *Progress In Electromagnetics Research C*, Vol. 104, 253–268, 2020.

[17] Errouas, Y., I. E. kadmiri, Y. Ben-Ali, and D. Bria, "Electromagnetic filtering and guiding of three frequencies by the presence of defects in one-dimensional photonic star waveguides structure," *Materials Today: Proceedings*, Vol. 45, 7734–7741, 2021.

[18] El-Aouni, M., Y. Ben-Ali, I. E. Kadmiri, Z. Tahri, and D. Bria, "Electromagnetic multi-frequencies filtering by a defective asymmetric photonic serial loops structure," in *Proceedings of the 2nd International Conference on Electronic Engineering and Renewable Energy Systems*, 195–202, Springer, Singapore, 2021.

[19] Limonov, M. F., M. V. Rybin, A. N. Poddubny, and Y. S. Kivshar, "Fano resonances in photonics," *Nature Photonics*, Vol. 11, 543–554, 2017.

[20] Paul, S. and M. Ray, "Simultaneous switching at multiple wavelengths using plasmon induced transparency and fano resonance," *IEEE Photonics Technology Letters*, Vol. 29, No. 9, 739–742, 2017.

[21] Limonov, M. F., "Fano resonance for applications," *Advances in Optics and Photonics*, Vol. 13, No. 3, 703–771, Sep. 2021.

[22] Fan, H., H. Fan, and H. Fan, "Multiple fano resonance refractive index sensor based on a plasmonic metal-insulator-metal based taiji resonator," *Journal of the Optical Society of America B*, Vol. 39, No. 1, 32–39, Jan. 2022.

[23] Nguyen, V. A., Q. M. Ngo, and K. Q. Le, "Efficient color filters based on Fano-like guided-mode resonances in photonic crystal slabs," *IEEE Photonics Journal*, Vol. 10, No. 2, 2018.

[24] Cao, G., S. Dong, L.-M. Zhou, Q. Zhang, Y. Deng, C. Wang, H. Zhang, Y. Chen, C.-W. Qiu, and X. Liu, "Fano resonance in artificial photonic molecules," *Advanced Optical Materials*, Vol. 8, No. 10, 1902153, May 2020.

[25] Caselli, N., F. Intonti, F. L. China, F. Biccari, F. Riboli, A. Gerardino, L. Li, E. H. Linfield, F. Pagliano, A. Fiore, and M. Gurioli, "Generalized Fano lineshapes reveal exceptional points in photonic molecules," *Nature Communications*, Vol. 9, Jan. 2018.

[26] Limonov, M. F., "Fano resonance for applications," *Advances in Optics and Photonics*, Vol. 13, No. 3, 703–771, Sep. 2021.

[27] Mouadili, A., E. H. E. Boudouti, A. Soltani, A. Talbi, A. Akjouj, and B. Djafari-Rouhani, "Theoretical and experimental evidence

of Fano-like resonances in simple monomode photonic circuits," *Journal of Applied Physics*, Vol. 113, No. 16, 164101, Apr. 2013.

[28] Johansen, E. L., "Millimeter-wave radar," *Active Electro-Optical Systems*, Vol. 5, 1993.

[29] Liu, W.-C., "A coplanar waveguide-fed folded-slot monopole antenna for 5.8 GHz radio frequency identification application," *Microwave and Optical Technology Letters*, Vol. 49, No. 1, 71–74, Jan. 2007.

[30] Helou, W., M. Goniche, J. Hillairet, F. Zacek, J. Achard, J. Adamek, O. Bogar, P. Mollard, J.-Y. Pascal, S. Poli, D. Sestak, R. Volpe, and J. Zajac, "Radio-frequency design of a lower hybrid slotted waveguide antenna," *Fusion Engineering and Design*, Vol. 123, 223–227, Nov. 2017.

[31] Dimitriadis, A. I., T. Debogovic, M. Favre, M. Billod, L. Barloggio, J.-P. Ansermet, and E. De Rijk, "Polymer-based additive manufacturing of high-performance waveguide and antenna components," *Proceedings of the IEEE*, Vol. 105, No. 4, 668–676, Apr. 2017.

[32] Dobrzynski, L., "Interface response theory of continuous composite-materials," *Surface Science*, Vol. 180, No. 2-3, 489–504, Feb. 1987.

[33] El Boudouti, E. H., N. Fettouhi, A. Akjouj, B. Djafari-Rouhani, A. Mir, J. O. Vasseur, L. Dobrzynski, and J. Zemmouri, "Experimental and theoretical evidence for the existence of photonic bandgaps and selective transmissions in serial loop structures," *Journal of Applied Physics*, Vol. 95, No. 3, 1102–1113, Feb. 2004.