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A FOURTH-ORDER SIW BANDPASS FILTER WITH OPTIMIZED PASSBAND PERFORMANCE FOR MILLIMETER-WAVE APPLICATIONS

BỘ LỌC THÔNG DẢI SIW BẬC BỐN VỚI HIỆU SUẤT DẢI THÔNG ĐƯỢC TỐI ƯU HÓA CHO CÁC ỨNG DỤNG SÓNG MILIMET

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Abstract:

This paper presents the design of a four-order substrate integrated waveguide (SIW) bandpass filter optimized for millimeter-wave wireless applications. SIW technology balances loss, cost, and integration capabilities while achieving high selectivity and a compact form factor in RF/Microwave filter design. Since SIW primarily operates in the dominant TE_{10} mode, the electric field E has a maximum value located on the vertical central plane and along the propagation direction. Therefore, the central plane can be considered an equivalent magnetic wall. The proposed filter is composed of four SIW resonators connected in series. The simulated results show that the fourth-order SIW filter has a center frequency of 26 GHz with 3 dB bandwidth of about 4.67 GHz. The achieved minimum insertion loss in the passband is 1.1 dB, and return loss is better than 20 dB. The passband ripple is significant reduced to below 1dB, while the out-band rejection is better than 20 dB from 22 to 23.1 GHz which improved the selectivity of the filter. This filter is suitable for millimeter-wave wireless systems such as 5G, automotive radar, and satellite communication due to its high selectivity, low loss, and compact size.

Keywords:

Substrate integrated waveguide, Bandpass filter, Four-order filter, Millimeter-wave.

Tóm tắt:

Bài báo trình bày thiết kế một bộ lọc thông dải bậc bốn sử dụng công nghệ đường dẫn sóng tích hợp trên chất nền (SIW) ứng dụng trong dải tần sóng milimet. Công nghệ SIW có khả năng cân bằng giữa tổn hao, chi phí và khả năng tích hợp, đồng thời đạt được độ chọn lọc cao và kích thước nhỏ gọn trong thiết kế các bộ lọc siêu cao tần. Vì SIW chủ yếu hoạt động ở chế độ TE_{10}, nên trường điện E đạt giá trị cực đại tại mặt phẳng đứng trung tâm và dọc theo hướng truyền sóng. Do đó, mặt phẳng trung tâm có thể được coi như một tường từ tương đương. Bộ lọc được đề xuất bao gồm bốn bộ cộng hưởng SIW mắc nối tiếp. Kết quả mô phỏng bộ lọc thông dải SIW bậc bốn được đề xuất hoạt động ở tần số trung tâm 26 GHz với băng thông 3 dB khoảng 4,67 GHz. Tổn hao chèn nhỏ nhất đạt được trong dải là 1,1 dB, và tổn hao phản hồi nhỏ hơn -20 dB. Độ nhấp nhô trong dải giảm đáng kể xuống dưới 1 dB, trong khi khả năng triệt tiêu ngoài dải được cải thiện với mức suy giảm dưới -20 dB trong dải tần từ 22 đến 23,1 GHz, góp phần nâng cao độ chọn lọc của bộ lọc. Bộ lọc đề xuất phù hợp cho các hệ thống không dây sóng milimet như 5G, radar và thông tin vệ tinh nhờ độ chọn lọc cao, tổn hao thấp và kích thước nhỏ gọn.

Từ khóa:

Ống dẫn sóng tích hợp trên chất nền, Bộ lọc thông dải, Bộ lọc bậc bốn, Sóng milimet.

1. INTRODUCTION

In millimeter-wave applications, stripline circuit implementations are generally ineffective, as the short wavelengths at high frequencies impose extremely small feature dimensions and stringent fabrication tolerances. Therefore, at high-frequency ranges, devices made on traditional waveguides are preferred; however, their production is challenging. A new technology has been researched and applied, known as Substrate Integrated Waveguide (SIW). SIW is a transition between strip circuit technology and dielectric-filled waveguides (DFW). DFWs are converted into SIWs using the assistance of vias for the waveguide sidewalls.

Substrate technology has been widely applied to microwave components, especially filters, with different SIW structures. SIW technology applied to filters developed in recent years has created the best balance between loss and cost compared to filters based on stripline technology and classical waveguide technology [1-5]. SIW bandpass filters would be a very good compromise between a bandpass filter on microstrip and a bandpass filter on a waveguide, especially in the high frequency range because SIW technology has a high Q factor, small size, easy to manufacture and easy to integrate with other components [6]. However, for bandpass filters that require a wide bandwidth, SIW technology does not meet that requirement [7].

A fourth-order SIW filter is proposed in this paper. The empirical equation for SIW geometric parameters provides enhanced accuracy over previous methods. The proposed design improves the selectivity and efficiency of bandpass filters, particularly for millimeter-wave wireless applications, with advantages such as ease of manufacturing and integration with other planar RF microwave circuits.

2. FILTER DESIGN AND THEORETICAL ANALYSIS

A. Rectangular SIW Structure

In general, the geometric structure of SIW is illustrated through a standard rectangular SIW structure as shown in Figure 1, while other structural forms (circular, triangular, polygonal, etc.) have similar characteristics and analysis methods. Rectangular SIW is characterized by three parameters: width *W*, via diameter *d*, and spacing between vias *s* as illustrated in Figure 1.

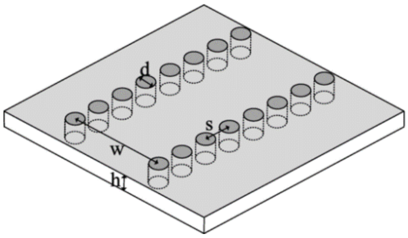


Figure 1. Configuration of rectangular SIW

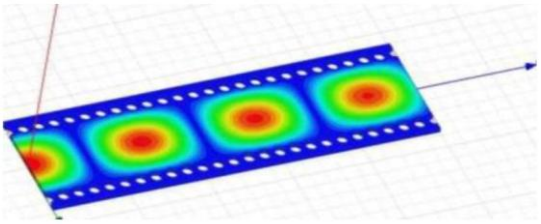
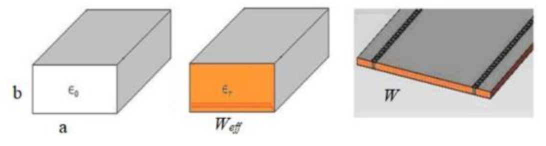


Figure 2. Electric field strength of the fundamental mode in SIW



(a) (b) (c)

Figure 3. SIW structure development. (a) Air-filled rectangular waveguide. (b) Dielectric-filled rectangular waveguide. (c) Substrate-integrated waveguide

The electromagnetic field propagation characteristics of rectangular SIW resemble those of traditional rectangular metallic waveguides, provided that the vias are closely spaced, allowing radiation leakage to be neglected, as is displayed in Figure 2. Specifically, the dominant mode of wave propagation in SIW is also the TE_{10} mode, with longitudinal current density on the sidewalls. Rectangular SIW is a new form of transmission line with electromagnetic waves, resembling a DFW with a much smaller height compared to its width ($b << W_{eff}$) as shown in Figure 3. Due to the presence of vias on the sidewalls of the rectangular SIW, transverse magnetic (TM) modes do not exist; thus, the dominant mode in rectangular SIW is the TE_{10} mode, similar to air-filled waveguides.

As shown in Figure 3, SIW can be considered a form of DFW, starting from DFW. For the TE_{10} mode, the term "*b*" is not important as it does not affect the waveguide's cutoff frequency. Therefore, the substrate can have any thickness, only affecting the dielectric loss. This issue will be clarified in the following equation.

For rectangular waveguide, the cutoff frequency of any mode is given by the following equation [9]:

$$f_{cmno} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \qquad (1)$$

The cutoff frequency of a mode with $\mu_r = 1$ and $\varepsilon_r = 1$ is given by:

$$f_c = \frac{c}{2\pi} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \qquad (2)$$

where *c* is the speed of light in free space, *m* and *n* are the mode indices, *a* is the length, and *b* is the width of the rectangular waveguide.

Since the dominant mode in rectangular waveguide is the TE_{10} mode, the simplest equation for the cutoff frequency is:

$$f_c = \frac{c}{2\pi} \qquad (3)$$

For the same cutoff frequency, the equivalent width W_{eff} of the DFW is:

$$W_{eff} = \frac{a}{\varepsilon_r} \qquad (4)$$

where ε_r is the dielectric constant of the material filling the rectangular waveguide. Using these conditions and for SIW to operate at the same cutoff frequency f_c (i.e., the TE_{10} dominant mode of SIW), the first intial design formula relating to the width *W* of SIW can be determined from the corresponding resonant frequency:

$$f_{TE_{10}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{1}{W_{eff}}\right)^2 + \left(\frac{1}{L_{eff}}\right)^2} \qquad (5)$$

where L_{eff} is the equivalent length of DFW. Therefore, the design equation for SIW will be:

$$W = W_{eff} + \frac{d^2}{0.95s} \qquad (6)$$

For *d* and *s* to satisfy the condition:

$$d < \frac{\lambda_g}{5} \text{ and } \frac{s}{d} \le 2 \qquad (7)$$

where λ_g is the guided wavelength in the dielectric material, which is related to the effective width of the DFW and is calculated as follows [15]:

$$\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_r (2\pi f)^2}{c^2} - \left(\frac{\pi}{a}\right)^2}} \tag{8}$$

Finally, the normalized relation in (6) is expressed as:

$$W = W_{eff} + 1.08\frac{d^2}{s} - 0.1\frac{d^2}{W} \tag{9}$$

B. SIW Bandpass Filter Design

The filter is designed for a center frequency of 26 GHz, with a 3-dB bandwidth of 4.67 GHz. The passband ripple is smaller 1 dB, while the required out-of-band rejection is ≥ 20 dB in the 22–23.1 GHz range. The filter design process follows the standard synthesis approach for Chebyshev bandpass filters, where the electrical performance is dictated by the filter order, external quality factor, and coupling coefficients. The filter order *N* is determined based on the required bandwidth and rejection characteristics. Using the classical filter approximation method, the order is estimated as fourth-order.

The dominant mode in an SIW filter is the TE_{10} mode, which defines how electromagnetic waves propagate. The cutoff frequency of this mode in an SIW is given by [16]:

$$f_c = \frac{c}{2a_{eff}\sqrt{\varepsilon_r}} \tag{10}$$

The operating frequency of the bandpass filter must be above the cutoff frequency to ensure proper wave propagation.

The equivalent rectangular waveguide is defined using the effective width a_{eff} as:

$$a_{eff} = a - \frac{d^2}{0.95s} \tag{11}$$

where: a is the physical width of the SIW, d is the diameter of the metallic vias, s is the center-to-center distance between adjacent vias.

Assuming the physical width a = 5.5 mm, via diameter d = 0.6 mm and via pitch s = 1.2 mm, we can obtain the effective width a_{eff} is calculated approximately 5.2 mm.

The physical realization of the design SIW BPF involves selecting the number of resonators, their spacing, and coupling mechanisms. The design SIW cavity resonator is formed by enclosing a section of the waveguide with conductive vias. The resonant frequency of an SIW cavity follows:

$$f_{mn} = \frac{c}{2}\sqrt{\left(\frac{m}{a_{eff}}\right)^2 + \left(\frac{n}{b_{eff}}\right)^2} \tag{12}$$

For a fourth-order bandpass filter, four coupled resonators are cascaded, ensuring a steeper roll-off and better selectivity.

The coupling between the resonators is primarily controlled by the width and length of the resonator. When the resonators are coupled together, the peak of the center frequency of one resonator splits into two distinct peaks. Therefore, the coupling coefficient of two adjacent resonators can be obtained from the simulated scattering parameters of the two resonators and can be written as [10]:

$$k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{13}$$

Where f_1 and f_2 are the frequencies at which the coupled resonators resonate.

The inter-resonator coupling coefficients are calculated using:

$$k_{i,i+1} = \frac{BW}{\sqrt{g_i g_{i+1}}} \tag{14}$$

where low-pass prototype values for a fourth-order Chebyshev filter are:

$g_0 = 1, g_1 = 1.371, g_3 = 0.726, g_4 = 1$ [9].

From this, the coupling coefficients are $k_{12} = k_{23} = k_{34} = 0.145$. The external quality factor Qe is given by:

$$Q_e = \frac{g_0 g_1}{BW / f_c} = 4.04 \qquad (15)$$

A configuration of four-order SIW bandpass filter with Chebyshev frequency response is depicted in Figure 4. The coupling topology of the four-order bandpass filter is shown in Figure 5. Each node stands for an SIW cavity.

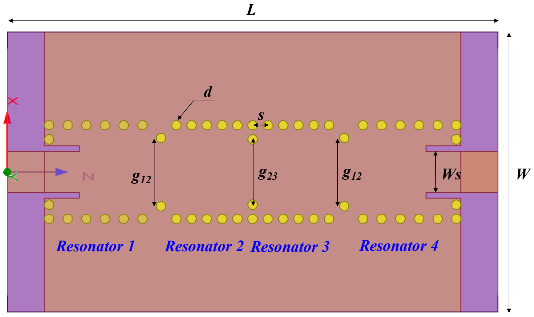


Figure 4. Geometric configuration of the proposed SIW filter

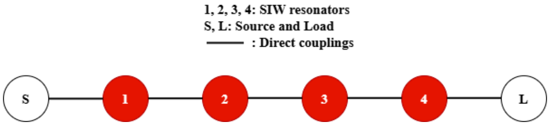


Figure 5. Coupling topology of four-order SIW bandpass filter with Chebyshev frequency response

The coupling diagram will provide the requirements for the input and output to be achieved by analyzing a single resonator. The coupling degree between the resonators is mainly controlled based on the length and the width of the component resonators. When the resonators combine, by changing the parameters of the component resonators using HFSS simulation software, we can determine the center frequency and the scattering parameters of the filter.

The four-order SIW bandpass filter with Chebyshev frequency response is synthesized at 26 GHz with a 3-dB fractional bandwidth of 17.9%.

The design steps for an SIW bandpass filter can be summarized as follows:

- Step 1: Establish the technical parameters of the filter;
- Step 2: Select the substrate material used in the filter design;
- Step 3: Determine the number of filter order appropriate for the given specifications;
- Step 4: Determine the center frequency, cutoff frequency, and filter dimensions;
- Step 5: Perform simulations to adjust and optimize the parameter values.

3. FILTER IMPLEMENTATION AND RESULTS

For the design of a millimeter-wave bandpass filter with the above technical requirements, the selected substrate material is Rogers 4350 dielectric substrate with a thickness of 0.762 mm (ε_r = 3.66; tan δ = 0.004). The initial dimensions of the fourth-order SIW filter can be calculated based on above analysis and carried-out by full-wave electromagnetic Ansys HFSS simulation software. The simulated coupling coefficients g_{12} and g_{23}, shown in Figure 6 and Figure 7, have a significant impact on the S-parameters of the proposed SIW bandpass filter.

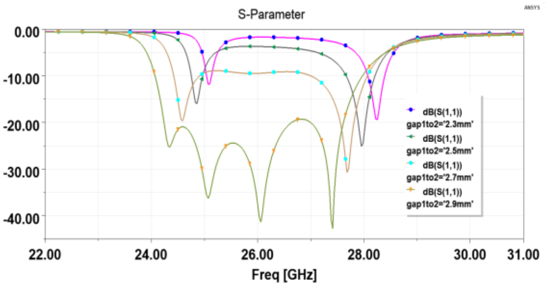


Figure 6. S11 simulated results of proposed SIW bandpass filter with variation g_{12}

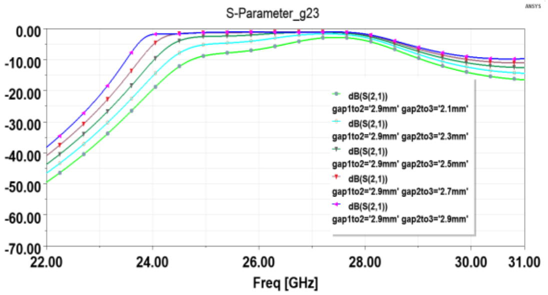


Figure 7. S_{21} simulated results of proposed SIW bandpass filter with variation g_{23}

In Figure 6, g_{12} varies from 2.3 mm to 2.9 mm, and g_{23} ranges from 2.1 mm to 2.9 mm, affecting the bandwidth and impedance matching, where stronger coupling leads to a wider passband and reduced return loss. Figure 7, focuses on the effect of g_{23}, demonstrating how its variation impacts the passband response and stopband rejection. The variations in S-parameters between the two figures demonstrate the importance of tuning g_{12} and g_{23} to minimize insertion loss, improve return loss, and enhance selectivity. After carefully tuning, the performance of the proposed filter has been optimized to approach the specifications. The final dimensions of proposed filter (in mm) are listed in Table 1.

Table 1. Dimensions of the four-order SIW bandpass filter with Chebyshev frequency response

Parameters	Value
W	12
L	21
W_s	1.76
d	0.4
g_{12}	2.91
g_{23}	2.79
s	1.1

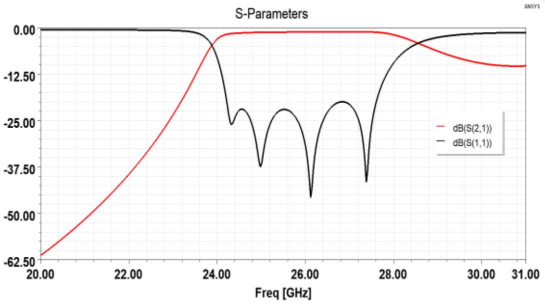


Figure 8. Simulated S-parameters of four-order SIW bandpass filter

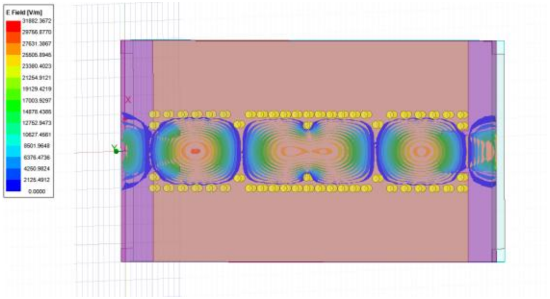


Figure 9. Simulated *E*-field distributions of four-order SIW bandpass filter

As shown in Figure 8, the simulated results show that the fourth-order SIW filter has a center frequency of 26 GHz with 3 dB bandwidth of about 4.67 GHz. The minimum insertion loss in the passband is 1.1 dB, and the passband return loss is better than 20 dB. The ripple inband is below 1dB, while the out-band rejection is below -20dB from 22 to 23.1 GHz which improved the selectivity of the filter. Figure 9 depicts verified E-field distributions of four-order SIW bandpass filter. Table 2 shows the comparison of the simulated features of the proposed SIW bandpass filter with other works. The proposed SIW filter achieves better suppression of unwanted frequencies and lower insertion loss with [11] but has a more complex fabrication process due to enhanced via-hole structuring. Compared to [12] and [14], the proposed filter is more compact while maintaining performance, making it suitable for 5G applications; however, its miniaturization increases

Table 2. Comparison of the simulated features of the proposed SIW bandpass filter

Ref.	Center Frequency (GHz)	FBW (%)	IL (dB)	RL (dB)	Size (mm)
[11]	13.7	5.8	2.5	15	40 x 24
[12]	25.25	3.56	0.79	12	30 x 19.5
[13]	27	3.7	1.2	25	15 x 6
[14]	23.45	35	0.5	20	12.7 x 7
This work	**26**	**17.9**	**1.1**	**20**	**21 x 12**

***FBW: Fractional Bandwidth, IL: Insertion Loss, RL: Return Loss**

sensitivity to fabrication tolerances. Lastly, compared with [13], the proposed filter provides better bandwidth control, though with a narrower frequency response.

4. CONCLUSION

A fourth-order SIW filter is proposed in this paper. This filter is designed at the center frequency of 26 GHz with a 3-dB fractional bandwidth of 17.9%. In the passband, the minimum insertion loss is 1.1 dB, while the return loss is better than 20 dB. This work bridges the limitations of conventional strip circuits and dielectric-filled waveguides by implementing SIW technology. It offers high selectivity, compact size, and easy integration with other planar RF microwave circuit. These results present the SIW filter as a promising solution for millimeter-wave wireless communications.

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REFERENCES

[1] Chen R.S., Xiao-Ping, and Wu K., Substrate Integrated Waveguide Filter: Basic Design Rules and Fundamental Structure Features, Microwave Magazine, IEEE 15.5,: pp. 108-116, 2014.

[2] Grigoropoulos N., Izquierdo B.S., Young P.R., Substrate integrated folded waveguides (SIFW) and filters, IEEE Microw. Wirel. Compon. Lett., pp. 829 – 831, 2005.

[3] Mohammad Almalkawi, et al, Design of a dual-band dualmode substrate integrated waveguide filter with symmetric transmission zeros, Applied Electromagnetics Conference (AEMC), 2011 IEEE, pp. 978-980, 2011.

[4] Rezaee M. and Attari A. R., A novel mode dual band SIW filter, European Microwave Conference (EuMC), pp. 853-857, 2014.

[5] Shen Wei, Yin Wen-Yan, and Sun Xiao-Wei, Miniaturized dualband substrate integrated waveguide filter with controllable bandwidths, Microwave and Wireless Components Letters, pp. 418-420, 2011.

[6] T. V. Duong, W. Hong, Z. C. Hao, W. C. Huang, J. X. Zhuang and M. H. Nguyen, A new class of selectivity-improved mm-waves dual-mode substrate integrated waveguide filters, 2015 Asia-Pacific Microwave Conference (APMC), Nanjing, China, 2015, pp. 1-3.

[7] Deslandes D., Wu K., Single substrate integration technique of waveguide filters, IEEE Trans. Microw. Theory Tech., pp. 593-596, 2003.

[8] Guha D., Biswas S., and Antar Y. M. M., Defected Ground Structure for Microstrip Antennas, in Microstrip and Printed Antennas: New Trends, Techniques and Applications, JohnWiley & Sons, London, UK, pp. 307-434, 2019.

[9] J.-S. Hong and M. J. Lancaster, Microstrip Filters for RF/Microwave Applications. Hoboken, NJ, USA: Wiley, 2004.

[10] Pozar D. M, Microwave Engineering, Fourth edition. New York: John Wiley & Sons, 2009.

[11] O. I. Hussein et al., Substrate Integrated Waveguide Bandpass Filtering With Fourier-Varying Via-Hole Walling, in IEEE Access, vol. 8, pp. 139706-139714, 2020.

[12] Jian-Mei Huang, Hai-Tao Xing, and Zhong-Hua Ma, Substrate-integrated Waveguide Bandpass Filter for 5G Applications, Sensors and Materials, vol. 36, no. 3, pp. 1105–1113, 2024.

[13] Banu priya A, Umma Habiba H, Design and analysis of full mode SIW bandpass filter for 5G applications, International Journal of Creative Research Thoughts, vol. 44, no. 1, pp. 1-4, 2022.

[14] Venmathi A R, Murugesan K, Srividhya K, Shally S P, Miniaturized Substrate-Integrated Waveguide Bandpass Filter Using Symmetric Vertical Slots, International Journal for Multidisciplinary Research, vol. 6, issue 5, pp. 1-9, 2024.

[15] Arnieri E., AmendolaG., Analysis of Substrate Integrated Waveguide Structures Based on the Parallel-Plate Waveguide Green's Function, IEEE Trans. Microw. Theory and Techn., pp. 1615-1623, 2008.

[16] Salehi M. and Mehrshahi E., A closed-form formula for dispersion characteristics of fundamental SIW mode, IEEE Microwave Wireless Comp. Lett., pp. 4-6, 2011.

Biography:

Le Trong Hieu was born in Hanoi, Vietnam in 1986. He graduated at Le Quy Don Technical University in Electronics and Telecommunications, in June 2009. He received the M.Sc. and Ph.D. degrees in Electromagnetic Field and Microwave Technology from the State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, Nanjing, China, in 2013 and 2018, respectively. Now, he is currently a lecturer in the Faculty of Electronics and Telecommunications, Electric Power University, Hanoi, Vietnam.

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