Progress In Electromagnetics Research Letters, Vol. 90, 45–51, 2020

A Compact Negative-Group-Delay Microstrip Bandpass Filter

Zhongbao Wang*, Zheng Fu, Chengze Li, Shaojun Fang, and Hongmei Liu

Abstract—In this paper, a compact negative-group-delay (NGD) microstrip bandpass filter is proposed. The NGD characteristic is achieved by coupling a resistor-loaded microstrip line to a square open-loop resonator. To improve the selectivity, the square open-loop resonator is loaded with an open-circuited stub for realizing two transmission zeros (TZs) in the upper stopband. To verify the proposed method, an NGD microstrip bandpass filter with a size of $0.58\lambda_g \times 0.35\lambda_g$ is designed and fabricated. From the measured results, the NGD time of -1.08 ns at the center frequency of 1.995 GHz is obtained with the NGD bandwidth of 34 MHz (1.977–2.011 GHz), in which the insertion loss is less than 7.5 dB, and the return loss is greater than 20 dB. Furthermore, three TZs at 1.520, 2.495, and 2.735 GHz are achieved with good stopband attenuation.

1. INTRODUCTION

The bandpass filter is an essential component in the microwave technology field. Among various types of bandpass filters, microstrip bandpass filter is more widely used due to its advantages of compact size, low cost, and easy fabrication. Currently, the researches on bandpass filters include ultra-wideband bandpass filters, multi-band, tunable, harmonic suppression, balanced ports, and integration with power dividers and couplers [1–3]. However, the investigation of the group delay in these circuits is lacking. Moreover, conventional bandpass filters generally provide only positive group delay.

Recently, negative group delay (NGD) microwave circuits have attracted much attention due to their practical and potential applications in a variety of microwave systems [4–7]. They have been used to shorten or eliminate delay lines [8], compensate the group delay of the ultra-wideband amplifier [9], enhance the efficiency of the cross-cancellation power amplifier [10], realize the non-Foster reactive elements [11], and minimize beam-squint in phased array antenna systems [12]. Especially, a design for increasing the efficiency of the feed-forward power amplifier by the NGD circuit is proposed in [13]. Besides, the NGD circuit is also used to broaden the bandwidth of an analog feedback power amplifier [14]. It is noted that in these amplifiers [13, 14], the NGD circuit requires a bandpass filter before it, which is used to avoid oscillations at unwanted frequencies. If we can design an NGD circuit with bandpass filtering, the size of these amplifiers will be effectively decreased. Therefore, the design of a bandpass filter with NGD characteristic in the passband has practical application significance in improving the performance of microwave systems and miniaturization of circuit topology. In [15, 16], NGD filters have been proposed and investigated. However, the NGD characteristics of these filters are accomplished in the stopband, which cannot be applied to the feed-forward and feed-back power amplifiers [13, 14] for performance enhancement and size reduction.

In this paper, a compact NGD microstrip bandpass filter is proposed. Bandpass filtering is implemented by two square open-loop resonators. Each of the square open-loop resonators is coupled with one resistor-loaded short-circuited microstrip line for obtaining the NGD characteristic in the passband. To improve the selectivity, a square open-loop resonator is loaded with an open-circuited

Received 27 December 2019, Accepted 8 February 2020, Scheduled 27 February 2020
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stub for realizing two transmission zeros (TZs) in the upper stopband. An NGD bandpass filter is designed to validate the proposed method.

2. FILTER STRUCTURE AND DESIGN

Figure 1 shows the proposed configuration of the NGD microstrip bandpass filter, which consists of two $\lambda/4$ resistor-loaded microstrip lines and two $\lambda/2$ square open-loop resonators loaded with open-circuited stubs. One end of the $\lambda/4$ resistor-loaded microstrip line is short-circuited, and the other end is open. The resistor R is grounded. The coupling between the $\lambda/4$ resistor-loaded microstrip line and $\lambda/2$ square open-loop resonator is used to obtain the NGD characteristic in the passband. The open-circuited stub is used to realize TZs in the upper stopband for improving the selectivity.

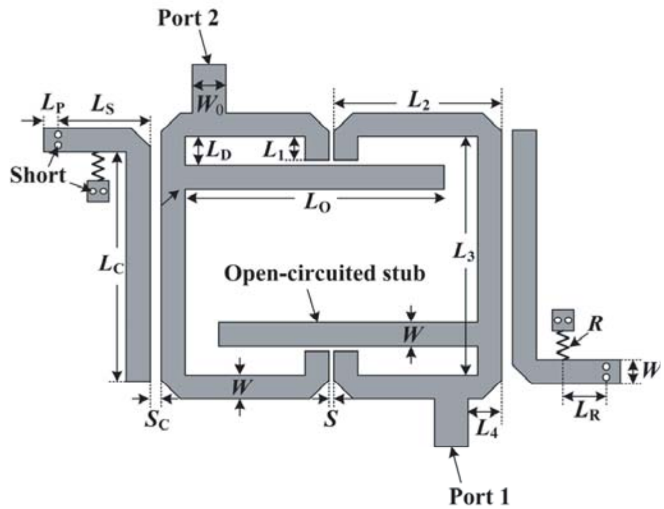

Figure 1. Configuration of the proposed NGD bandpass filter.

The NGD characteristic of the proposed bandpass filter is generated by the $\lambda/4$ resistor-loaded microstrip line, which is equivalent to an RLC resonator (i.e., a lossy resonator). Owe to the lossy microstrip resonator, the NGD characteristic is obtained. The NGD time is mainly determined by the loaded resistor and the coupling between the lossy microstrip resonator and square open-loop resonator. Figure 2 gives the effect of the loaded resistance R on the group delay and insertion loss of the proposed NGD bandpass filter. It is observed that when the loaded resistance R becomes larger, the absolute value of the NGD time at the center frequency of 2.0 GHz and insertion loss of the proposed NGD bandpass filter both become larger. Thus, there is a trade-off between the NGD time and insertion loss. Figure 3 gives the effect of the location of the loaded resistor (L_R) on the performances of the proposed NGD bandpass filter. It is seen that the loaded resistor is closer to the short point of the $\lambda/4$ resistor-loaded microstrip line, and the absolute value of the NGD time at the center frequency of 2.0 GHz and insertion loss of the proposed NGD bandpass filter both become larger. The changing location of the loaded resistor has no effect on the NGD center frequency.

Figure 4 gives the effect of the coupling factor k between the resistor-loaded microstrip line and square open-loop resonator on the performances of the proposed NGD bandpass filter. It is found that the maximum absolute value of the NGD time increases with the increase of the coupling factor k, but the insertion loss also increases, and the NGD center frequency decreases. The frequency shifting can be compensated by tuning the length of the coupled lines (i.e., L_C), as shown in Figure 5.

Figure 6 compares $|S_{21}|$ of the proposed NGD bandpass filter with and without the open-circuited stub. It is seen that two TZs are obtained in the upper stopband near 2.50 and 2.72 GHz by adding the open-circuited stub on the square open-loop resonator. The length of the open-circuited stub L_O is about $\lambda/4$ with respect to the third TZ operating frequency (about 2.72 GHz). Furthermore, the TZ in the lower stopband near 1.5 GHz is generated by the square open-loop resonator.

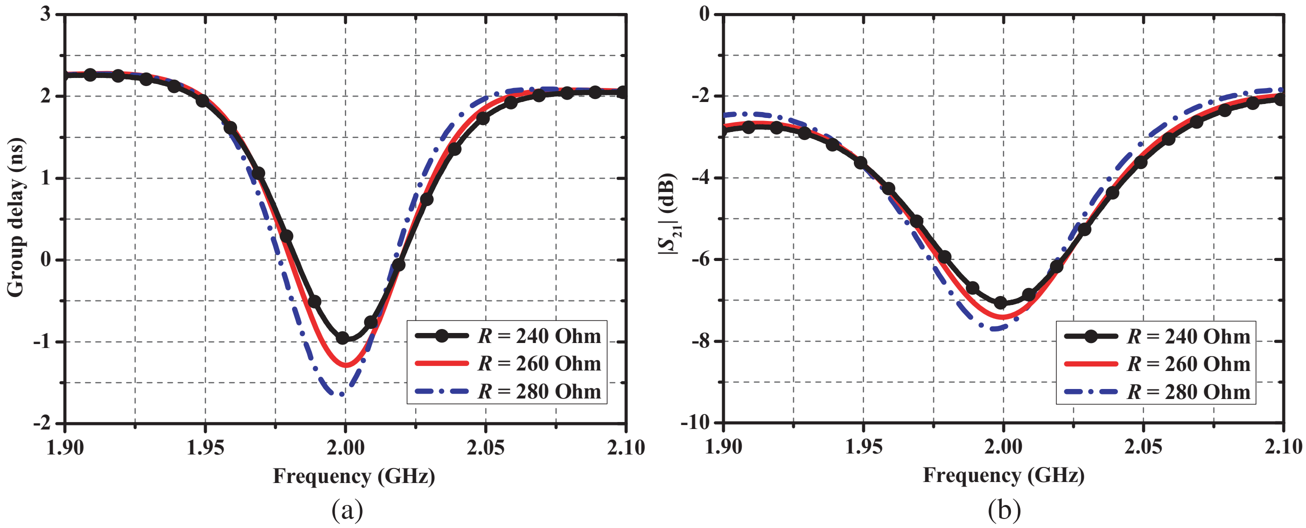

Figure 2. Effect of R on the performances of the proposed NGD bandpass filter. (a) Group delay. (b) $|S_{21}|$.

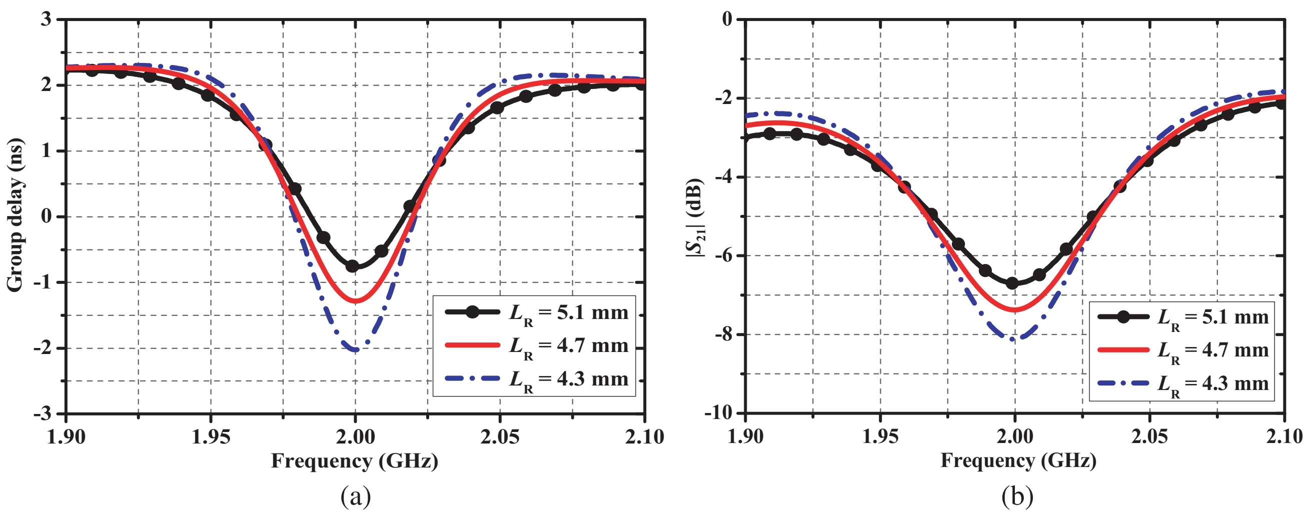

Figure 3. Effect of L_R on the performances of the proposed NGD bandpass filter. (a) Group delay. (b) $|S_{21}|$.

Based on the foregoing analysis studies, the following procedures are suggested to design the proposed NGD bandpass filter.

- 1) Determine the center frequency, NGD time, bandwidth, and TZ operating frequency according to the design requirements. Obtain the values of dielectric constant and thickness of the substrate material.
- 2) Select a proper microstrip width W and calculate the length of the resistor-loaded microstrip lines ($L_C + L_S$) to be about $\lambda/4$ and that of the square open-loop resonator ($2 \times L_1 + 2 \times L_2 + L_3$) to be about $\lambda/2$ with respect to the center frequency.
- 3) Calculate the length of the open-circuited stub (L_O) to be about $\lambda/4$ with respect to the third TZ operating frequency.
- 4) Choose a proper spacing between the square open-loop resonators (S and L_1) according to the bandwidth of the passband.

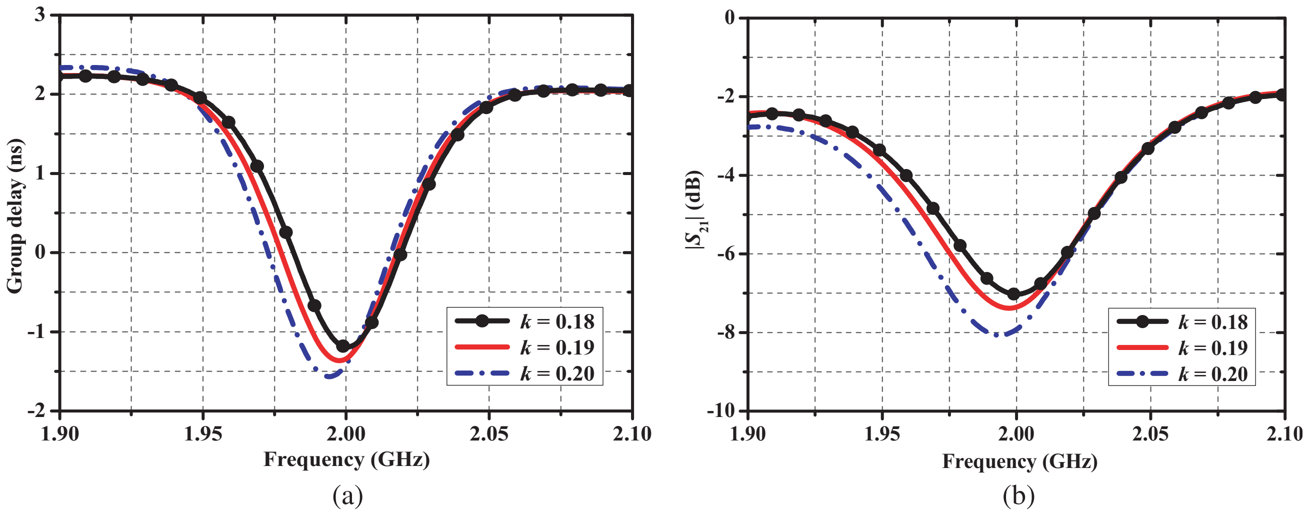

Figure 4. Effect of k on the performances of the proposed NGD bandpass filter. (a) Group delay. (b) $|S_{21}|$.

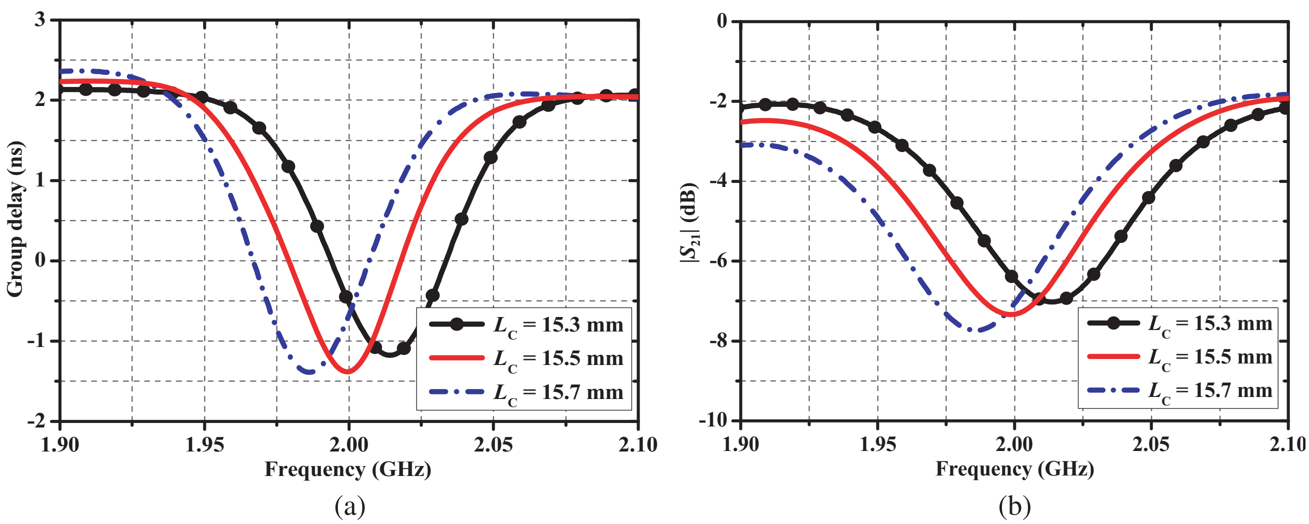

Figure 5. Effect of L_C on the performances of the proposed NGD bandpass filter. (a) Group delay. (b) $|S_{21}|$.

- 5) Determine the spacing between the coupled microstrip lines (S_C) according to the fabricating technology. Then select a proper length of the coupled microstrip lines (L_C) based on the required NGD time at the center frequency referring to Figure 5.
- 6) Select the loaded resistance R referring to the available resistors and Figure 2. Then adjust the location of the loaded resistor (L_R) to meet the NGD requirement referring to Figure 3.
- 7) Tune the physical dimensions to obtain the required performances using a full-wave electromagnetic simulator. If proper physical dimensions with the required performances cannot be realized, the design should be restarted from Step 2) with other potential values.

3. IMPLEMENTATION AND PERFORMANCE

To validate the proposed method, a compact 2.0-GHz NGD microstrip bandpass filter is designed and implemented on a 1.0 mm-thick substrate with a relative dielectric constant of 2.55. The HFSS EM

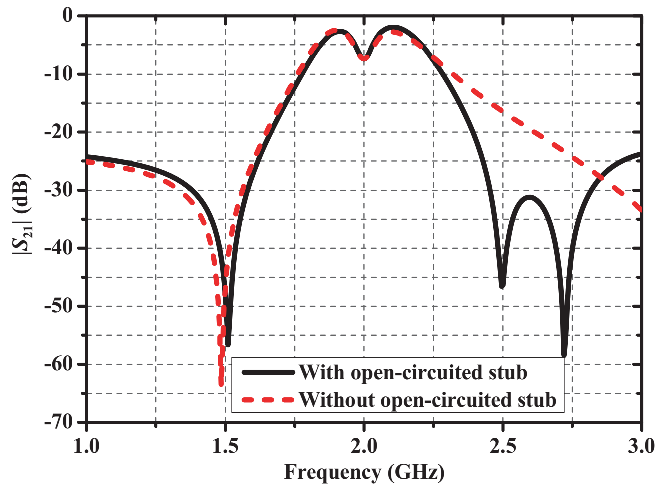

Figure 6. Comparison of the $|S_{21}|$ of the proposed NGD bandpass filter with and without the open-circuited stub.

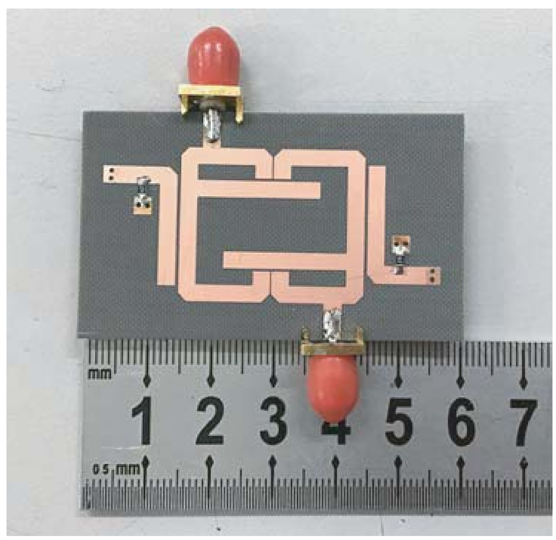

Figure 7. Photograph of the proposed NGD bandpass filter.

software is used to obtain the optimized dimensions. The dimensions of the NGD bandpass filter are found and implemented as follows: $W_0 = 2.89$ mm, $W = 2.65$ mm, $S = 0.18$ mm, $S_C = 0.49$ mm, $L_C = 15.51$ mm, $L_S = 9.90$ mm, $L_R = 4.70$ mm, $L_P = 1.45$ mm, $L_D = 2.45$ mm, $L_O = 19.00$ mm, $L_1 = 2.15$ mm, $L_2 = 14.20$ mm, $L_3 = 18.50$ mm, and $L_4 = 3.30$ mm with $R = 260$ Ohm. It is noted that only one parameter at a time is varied for the parametric analysis of Figures 2–6 in Section 2 by using the HFSS EM software, while the others are the same as the implemented values. A photograph of the fabricated NGD bandpass filter is shown in Figure 7. The overall dimension of the circuit is $60\,\text{mm} \times 36\,\text{mm}$ (around $0.58\lambda_g \times 0.35\lambda_g$, where λ_g is the guided wavelength of 50-Ω TLs at the center operating frequency).

To validate the design, S-parameters and group delay of the fabricated NGD bandpass filter are measured with an Agilent N5230A network analyzer. Figure 8 gives the simulated and measured group delays of the proposed NGD bandpass filter. It is observed that the NGD characteristic is achieved in the passband of the proposed filter. The measured NGD time is -1.08 ns at the center frequency of 1.995 GHz. And the measured NGD bandwidth of the proposed filter is 34 MHz from 1.977 to 2.011 GHz. Figure 9 gives the simulated and measured S-parameters of the proposed NGD bandpass filter. Three

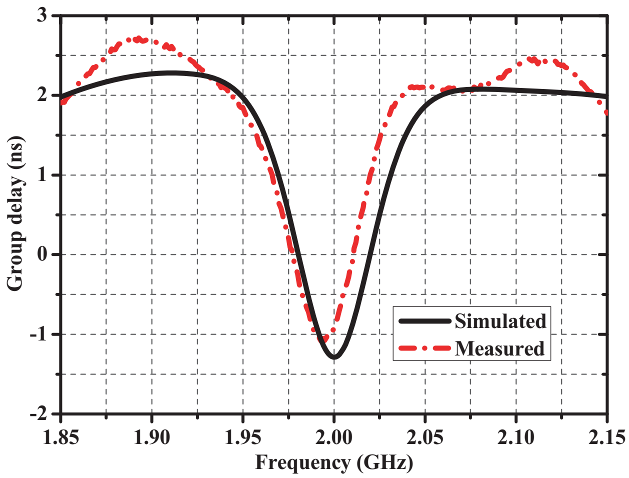

Figure 8. Simulated and measured group delay of the proposed NGD bandpass filter.

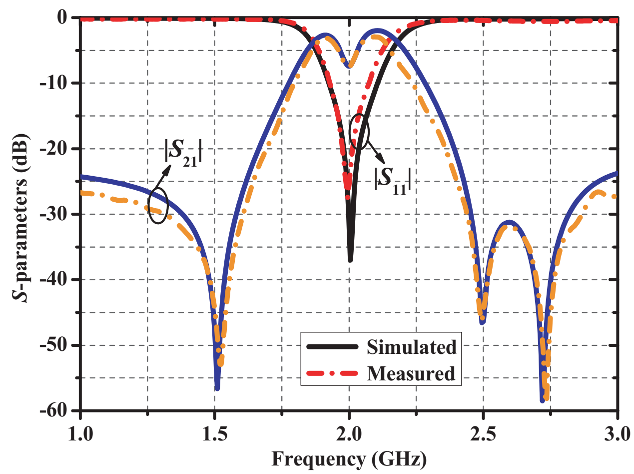

Figure 9. Simulated and measured S-parameters of the proposed NGD bandpass filter.

TZs at 1.520, 2.495, and 2.735 GHz are obtained by using square open-loop resonators added with open-circuited stubs. The measured stopband attenuation of the proposed NGD bandpass filter near the transmission zeros is more than 45 dB. The measured return and insertion losses in the NGD band are better than 20 dB and 7.5 dB, respectively. The measured return loss of more than 10 dB is in the frequency range from 1.93 to 2.07 GHz. There is some deviation between the simulated and measured results, which is mainly due to the fabrication tolerance.

4. CONCLUSIONS

In this paper, a compact NGD microstrip bandpass filter has been presented. The resistor-loaded microstrip line used to obtain the NGD characteristic for the bandpass filter has been investigated. Using square open-loop resonators added with open-circuited stubs, a high-selectivity bandpass filter with three TZs has been achieved. The proposed NGD bandpass filter can be applied to the feed-forward and feed-back power amplifiers [13, 14] for performance enhancement and size reduction.

ACKNOWLEDGMENT

This work was supported jointly by the National Natural Science Foundation of China (Nos. 61871417 and 51809030), the Natural Science Foundation of Liaoning Province (No. 2019-MS-024), the Youth Science and Technology Star Project Support Program of Dalian City (No. 2016RQ038), and the Fundamental Research Funds for the Central Universities (Nos. 3132019219 and 3132019211).

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