[Technical Paper]

Tunable Diplexer Composed of Asymmetric Hairpin Resonators Using Varactors with Constant Passband Bandwidth and High Isolation Characteristics

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Abstract

A tunable diplexer composed of asymmetric hairpin resonators using varactors with constant passband bandwidth and high isolation characteristics has been realized. A symmetric hairpin resonator loaded with a $(\text{Ba}_x\text{Sr}_{1-x})\text{TiO}_3$ (BST) varactor is proposed as a tunable resonator. It is matched to the frequency characteristics of bandpass filter (BPF) design parameters, namely, external quality factor and coupling coefficient. This resonator has a higher unloaded quality factor below 2 GHz than one using a silicon varactor diode. Also, beyond 2 GHz, the transmission characteristics of the proposed hairpin resonator loaded with a BST varactor are more stable. A tunable second-order BPF that maintains a constant bandwidth is configured using the proposed resonator. Those frequency characteristics are realized with only two BST varactors and a DC voltage supply. Finally, a configured and fabricated tunable diplexer using the proposed resonators is shown.

Keywords: Tunable Diplexer, Tunable Filter, Asymmetric Hairpin Resonator, BST Varactor, Constant Passband Bandwidth, High Isolation Characteristics

1. Introduction

As the number of wireless communication services increases, a radio frequency (RF) module is necessary to deal with the many signals. A tunable bandpass filter (BPF) can be tuned the operation frequency corresponding to each wireless communication service by adjusting the direct current (DC) voltages for varactor diodes, piezo elements, dielectric material rods, Micro Electro-Mechanical Systems (MEMS) capacitors, and so on. Nowadays, tunable multiplexers, which are composed of multiple filters, are focused on reconfigurable, multi-functional and multiband wireless communication systems for high speed and a large amount of information. Diplexers, which are a basic circuit configuration of multiplexers and composed of two filters, have been exhaustively researched for many years.[1–7] Rosenberg *et al.*[1] first presented a tunable multiplexer for broadcast satellites by tunable waveguided fourth-order elliptic-function BPFs using tuning plungers. Although it shows excellent performance, the multiplexer

is large since it is made of TE_{113} mode metal cavities. And, its frequency tunable range (*FTR*) is quite narrow, which is almost ± 50 MHz against center frequency of each BPF. *FTR* shows the range of minimum and maximum frequencies after the tuning is able to keep a constant bandwidth (*BW*) in each band. Miranda *et al.*[2] introduced a planar-type tunable diplexer made of gold and SrTiO_3 (STO) films on a LaAlO_3 (LAO) substrate. This was also pioneering research and showed good performance for tunable diplexers in the submillimeter wave band (20–30 GHz). However, it requires high applied DC voltages, which are 240 V from 80 V, for adjusting frequency characteristics. Djoumessi *et al.*[3] developed a planar-type tunable diplexer made of a printed circuit board (PCB) and silicon varactors. It was composed of tunable dual-mode resonators and realized large *FTRs* while maintaining a constant *BW*. The maximum value of *FTRs* is 2.62 to 3.3 GHz. Moreover, the conditions of the applied DC voltages are a few tenth of voltage against,[2] since silicon varactor diodes were used for the tuning. However, there are no design freedoms for miniaturization of the structure, namely

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there are only a few design parameters for structure design. Yang *et al.*[4] produced a compact planar-type tunable diplexer composed of tunable stepped impedance resonators (SIRs). Recently, Xu *et al.*[5] presented the most compact planar-type tunable diplexer composed of chip lumped elements, with three kinds of silicon varactor diodes. Li *et al.*[6] also developed a compact planar-type tunable diplexer with large FTR , which is 1.9 to 3 GHz, and very low deviation of BW for low- and high-band BPFs. In the most recent work by the same research group, a larger FTR , which is 2.2 to 3.5 GHz, of their simple structure was realized by maintaining the compact size and almost unchanging BW for each BPF.[7] This BW is defined as constant absolute bandwidth (ABW). However, it is quite difficult to configure a tunable diplexer structure with constant ABW and low insertion loss maintaining reasonable circuit size. Especially in,[5–7] complex design techniques are applied to configure the structure for tunable BPFs. The complex design techniques tend to require many varactors for accurate adjusting frequency characteristics so that it tends to be higher insertion loss. Therefore, it is significant to decrease the number of varactors and to select a suitable kind of varactor. Although silicon or gallium arsenide varactors are normally used, it is necessary to select a varactor after considering the frequency condition. Moreover, it is important to understand the performance of varactors and to fit a general BPF design technique which is based on external quality factor Q_e and coupling coefficient k .

In this paper, we attempted to realize a 1.6–2.91-GHz tunable diplexer with constant ABW using the minimum number of suitable varactor elements. Those frequency ranges are widely employed for wireless systems which are mobile phones, a personal handy-phone system (PHS), an industrial scientific and medical (ISM) band and so on. Therefore, a tunable frequency diplexing technique is needed for effective frequency usage. Firstly, a silicon varactor or a $(\text{Ba}_x\text{Sr}_{1-x})\text{TiO}_3$ (BST) varactor is selected by measuring and comparing the unloaded quality factor Q_0 for single resonators. To the best of our knowledge, those approaches which are determined a best candidate of a varactor by measurements and experimental comparisons of Q_0 s for a silicon and BST varactors have never been seen yet. It is a useful datum for designing tunable BPFs and diplexers. Secondly, a tunable asymmetric hairpin resonator loaded with a varactor element is proposed. This resonator is composed of uniform and stepped impedance transmission lines, considering the frequency characteris-

tics of Q_e and k . Thirdly, second-order BPFs with a constant ABW for the low-band and high-band using proposed resonators are configured. Finally, the results of the configured and fabricated tunable diplexers are shown.

2. Design of Tunable Resonators

2.1 Selection of varactors for a tunable resonator

The fabricated Uniform Impedance Resonators (UIRs) loaded with a silicon hyperabrupt junction varactor diode (Si-var) and a $(\text{Ba}_x\text{Sr}_{1-x})\text{TiO}_3$ (BST) varactor (BST-var) are shown in Fig. 1. The Si-var and BST-var were selected the ones with both of a broad range of capacitance and a low loss characteristic. An SMV1234 [8] and an STPTIC-82G2 [9] were selected as the Si-var and BST-var, respectively.

Fig. 1 (a) Fabricated tunable UIR loaded with a Si-var; (b) fabricated tunable UIR loaded with a BST-var.

Fig. 2 (a) Frequency characteristics of Fig. 1(a); (b) frequency characteristics of Fig. 1(b).

The C_{DC} , R and C_v represent the direct current (DC) cutting capacitor (1 nF), a bypass resistor (100 k Ω), and varactors, respectively. The capacitances of the Si-var and BST-var varies from 9.63 pF at 0 V to 1.32 pF at 15 V, and 11.5 pF at 0 V to 1.66 pF at 24 V, respectively. The relative dielectric constant ϵ_r , $\tan\delta$ and the thickness of the dielectric substrate are 3.4, 0.001, and 0.5 mm, respectively. Also, the conductivity and thickness of the conductor are 5.8×10^7 S/m and 18 μ m, respectively. The measured frequency characteristics for Fig. 1(a) and (b) are shown in Fig. 2. The resonant frequencies are changed by the input DC voltage until each maximum voltage of each varactor in both cases. The Si-var and other circuit elements are soldered by hand. Only the flip-chip package of the BST-var is soldered using cream solder heated by a hot plate. The degrading slope of S_{21} between 1.6 to 2.0 GHz in Fig. 2(a) is not steep compared with that in Fig. 2(b). Moreover, the calculated Q_0 is shown in Fig. 3. Q_0 is calculated by dividing a resonant frequency f_r of a resonator by the frequency width, which is defined by BW_{3dB} , between two frequency points degrading 3 dB from f_r , as follows:

Fig. 3 Calculated Q_0 from Figs. 2(a) and (b).

$$Q_0 = \frac{f_r}{BW_{3dB}}. \quad (1)$$

We found that the UIR loaded with a BST-var shows good performance below 2 GHz. Namely, the insertion loss (IL) of the designed BPF is lower. Also, the BST-var has another benefit, which is that it is not necessary to set a C_{DC} , since BST is an insulator. In Fig. 1(b), although a C_{DC} is set on the measured circuit, it is not necessary for tunable BPF and diplexer designs. This means that it is possible to attain a higher Q_0 than the one that found in the results of Fig. 3. Therefore, the BST-var was determined to be the best choice.

2.2 Design of asymmetric hairpin resonator loaded with a BST-var

It is necessary for the tunable BPF design to fit the frequency characteristics of design parameters by only changing the DC voltages of the BST-var. Q_e and k are utilized for the BPF design as design parameters. Q_e shows the degree of electromagnetic coupling among the input or output feed lines and a resonator, while k shows the degree of electromagnetic coupling between the resonators. Q_e is calculated by dividing f_{r-Qe} by BW_{3dB} , which is similar the case of Q_0 . f_{r-Qe} means a resonant frequency in the case of simulating a model as Fig. 5. k is calculated by dividing the difference of higher resonant frequency f_H and lower resonant frequency of f_L by the sum of f_H and f_L . The equations of Q_e and k are shown as follows:

$$Q_e = \frac{f_{r-Qe}}{BW_{3dB}}, \quad (2)$$

$$k = \frac{f_H - f_L}{f_H + f_L}. \quad (3)$$

Table 1 shows the design specifications and design parameters. The design parameters of Q_e and k at each frequency are determined based on filter synthesis theory. [10] Also, the relationship of the design parameters and

Fig. 4 Circuit structure of an asymmetric hairpin resonator.

Fig. 5 External quality factor simulation model.

Table 1 Design specifications and design parameters.

Frequency (GHz)	BW_{ripple} (GHz)	FBW	$Ripple$ (dB)	RL (dB)	$Q_{eS} = Q_{eL}$	k_{12}
1.5	0.135	0.0900	0.4	>10	15.11	0.09183
1.6	0.135	0.0844	0.4	>10	16.11	0.08609
1.7	0.135	0.0794	0.4	>10	17.12	0.08102
1.8	0.135	0.0750	0.4	>10	18.13	0.07652
1.9	0.135	0.0711	0.4	>10	19.14	0.07250
2.0	0.135	0.0675	0.4	>10	20.14	0.06887

circuit structures are explained in detail.[10] A designer will be able to configure a basic structure of BPF by referring to.[10] The BPF structure needs resonators and is determined by satisfying calculated Q_e and k . BW_{ripple} is set to 135 MHz to acquire almost 135 MHz of BW_{1dB} , considering the losses from the resonators. BW_{1dB} is defined as the frequency width between two frequency points below 1 dB from a maximum S_{21} characteristic. It is difficult to adjust Q_e and k in the case of a tunable UIR. Also, the area of a BPF is large. Therefore, we propose an asymmetric hairpin resonator loaded with a BST-var as the tunable resonator. Figure 4 shows the circuit structure of this resonator. The basic hairpin resonator is open-circuited end type distributed element resonator which resonates in the case the total length of it is a half of guided wavelength. A proposed resonator is composed of a uniform impedance transmission line and a stepped impedance transmission line, and it is folded into a hairpin shape. The frequency characteristics of electromagnetic couplings can be changed compared with the basic hairpin resonator since stepped impedance transmission lines are changed the capacitance and inductance of the resonator. As other features, a resonator using stepped impedance lines has unique features which are suppressed spurious characteristics and miniaturized a circuit size by controlling width of each transmission line.[11] As will be explained next, this structure has

Fig. 6 Simulated frequency characteristics of external quality factors for with and without square conductors.

features which are able to control the frequency characteristics of Q_e and k by combining a varactor. Figures 5 and 6 show an electromagnetic (EM) simulation model and the simulated results of Q_e with and without square conductors. Sonnet is used as the EM simulator.[12] Touchstone files of C_v with different applied DC voltage conditions are used as simulation models of it. In Fig. 6, the aimed line shows the approximate curve of Q_{eS} in Table 1. The feed lines form an open-circuited loop because the Q_e in Table 1 are consistent with an aimed line. Also, in Fig. 5, two square conductors attached to the feed line are effective for adjusting the slope and amount of Q_{eS} . In this time, although the Q_{eS} with and without the two square conduc-

(a)

(b)

Fig. 7 (a) Coupling coefficient simulation model using asymmetric hairpin resonators with a low impedance line; (b) coupling coefficient simulation model using conventional hairpin resonators.

Fig. 8 Coupling coefficient simulation results.

tors are almost same, the structure of the open-circuited loop feed lines loaded with two square conductors are employed since there is a high design freedom even if design specifications are changed. The a and b are equal to 2.2 and 0.3 mm, respectively. Figures 7 and 8 show an EM simulation model and the simulated results of k , respectively. In Fig. 8, the aimed line shows the approximate curve of k s in Table 1. The frequency characteristics of k for Fig. 7(a) almost match an aimed line due to the effects of the asymmetric resonator shape and a low impedance

Fig. 9 EM simulation model for tunable second-order BPF using asymmetric hairpin resonators.

Fig. 10 Simulation results for tunable second-order BPF using asymmetric hairpin resonators.

line. The ones for Fig. 7(b) are almost constant against frequency range except for a lowest frequency.

3. Design and Fabrication of a Tunable Second-order BPF

3.1 Design of a tunable second-order BPF

Figure 9 shows the circuit structure of a tunable second-order BPF using asymmetric hairpin resonators. The EM simulated results are shown in Fig. 10. When the BST-var capacitances vary from 8.2 pF at 2 V to 1.66 pF at 24 V, the center frequencies of the BPF change to 1.953 GHz from 1.506 GHz and maintain a BW_{1dB} of 142 MHz $\pm$ 22 MHz.

3.2 Fabrication and measurement of a tunable second-order BPF

Figure 11 shows a photograph of the fabricated tunable second-order BPF. This BPF applies DC voltages by only one DC voltage supply to two BST-vars. The measured results are shown in Fig. 12. When the DC voltages of BST-vars vary from 1.2 V to 24 V, the center frequencies of the BPF change to 2.009 GHz from 1.518 GHz and maintain a BW_{1dB} of 161 MHz $\pm$ 27 MHz. Table 2 shows a com-

Fig. 11 Photograph of the fabricated tunable second-order BPF using asymmetric hairpin resonators.

Fig. 12 Measured results for the fabricated tunable second-order BPF using asymmetric hairpin resonators.

Table 2 Comparison of EM simulated and fabricated second-order BPFs.

EM simulation				Measurement			
f_c (GHz)	BW_{1dB} (GHz)	FBW_{1dB}	IL (dB)	f_c (GHz)	BW_{1dB} (GHz)	FBW_{1dB}	IL (dB)
1.506	0.120	0.0797	2.56	1.518	0.133	0.0878	2.23
1.599	0.129	0.0807	2.36	1.612	0.140	0.0869	1.91
1.706	0.138	0.0809	2.22	1.704	0.147	0.0862	1.80
1.795	0.146	0.0813	2.27	1.820	0.162	0.0888	1.74
1.906	0.161	0.0845	2.47	1.897	0.175	0.0924	1.74
1.953	0.163	0.0835	2.51	2.009	0.188	0.0936	1.97

parison of EM simulated and measured results. FBW means a fractional bandwidth. The EM simulated results are in almost good agreement with the design specification, while the measured results of BW_{1dB} are broader. Also, return loss (RL) at lower edge frequency is degraded comparing with design specification. In Fig. 10, although RL s at lower and higher edge frequencies are degraded, the measured results of RL at higher frequency in Fig. 12 are improved. In the next section, we consider the reason for that difference.

3.3 Analysis and investigation of tolerance in the tunable second-order BPF

The reason for RL s at edge frequencies being degraded in Fig. 10 is investigated by comparing the calculated frequency characteristics using coupling matrix extractions of BPFs.[13] Figure 13 shows the extracted Q_e and k by EM simulated results and measured results. The causes of the degraded RL s at lower and higher edge frequencies in EM simulation or at lower edge frequency in measurement were found to be that Q_e and k on lower and higher edge frequencies are different from the aimed line. Especially, Q_e s are large differences from the aimed line. However, the quantitative influences of Q_e s and k s of the BPFs

Fig. 13 Extracted Q_e and k for tunable second-order BPF using asymmetric hairpin resonators.

are not found only comparisons of extracted values and the aimed values.

The tunable second-order BPF conditions of $RL > 9.5$ dB and 180.5 MHz (-5%) $< BW_{3dB} < 199.5$ MHz ($+5\%$) are investigated against matrix elements of a coupling matrix. In the case of second-order BPF, these elements are shown the self-coupling element namely the resonant frequency, the electromagnetic coupling element between two resonators, the electromagnetic coupling element between an

Fig. 14 Frequency characteristics at a center frequency of 1.7 GHz varying the elements of a coupling matrix.

input feed line and a resonator, and the electromagnetic coupling element between an output feed line and a resonator.[13] An L_8 orthogonal array in Robust Quality Engineering Society[14] is used to make a simulation procedure for varying the all matrix elements. The error bars in Fig. 13 represent the variable ranges of $\pm 4\%$ on each frequency after simulation using the L_8 orthogonal array. It was found that the above conditions are satisfied when the tolerances of elements are equal to $\pm 4\%$. As an example, Fig. 14 shows the frequency characteristics in the case of center frequency for 1.7 GHz when all elements are changed $\pm 4\%$ based on the L_8 orthogonal array. It is found that these results satisfy above conditions. When both the extracted Q_e and k are near the error bars in Fig. 13, the frequency characteristics in Figs. 10 and 12 are in almost good agreement with the design specification. In future works, it will be necessary to consider a circuit structure whose Q_e and k correspond with aimed lines, especially on edge frequencies.

In this work, although a detailed explanation of the design for a 2.5-GHz-band tunable second-order BPF, which is defined as high-band, is not provided, this high-band BPF is configured based on the same method shown in sections 2 and 3. Also, the frequency characteristics for its Q_e and k are nearer to the aimed line than those of Fig. 13. A detailed explanation can be found in.[15] In spite of the disadvantage of a BST-var over 1.95 GHz being lower Q_0 than that of a Si-var as shown in Fig. 3, BST-vars are used for the design of high-band BPFs because BPF characteristics for BST-vars are more stable. In next chapter, a tunable diplexer is configured using low- and high-band tunable second-order BPFs.

Fig. 15 Tunable diplexer simulation model.

4. Design and Measurement of a Tunable Diplexer

4.1 Design of a tunable diplexer

Figure 15 shows the designed circuit structure of a tunable diplexer. It is optimized using a circuit simulator before the values of chip elements in the matching circuits among port 1, the high-band BPF and the low-band BPF are determined. The EM simulated frequency characteristics adjusting DC voltages for only one side of the BPF are shown in Fig. 16. In both cases, each BPF characteristic without applied DC voltages in Fig. 16 shows almost no change, while the center frequencies for another BPF are varied. Also, the tunable diplexer maintains high isolation characteristics over 44 dB.

4.2 Measurement of the fabricated tunable diplexer

Figure 17 shows a photograph of the fabricated tunable diplexer. Also, the frequency characteristics are shown in Fig. 18. This diplexer applies DC voltages from two DC voltage supplies. The fabricated tunable diplexer operates in almost the same way as in the EM simulated results. Also, an isolation characteristic between the low- and high-band BPFs, S_{32} , shows good performance.

Finally, benchmarking of the tuning diplexer is shown in Tables 3 and 4. In Tables 3 and 4, Yang *et al.*[16] showed a tunable diplexer using a tunable common resonator and tunable UIRs. Chen *et al.*[17] showed a tunable diplexer using varactor-tuned dual-mode stab-loaded resonators. Ko *et al.*[18] showed a tunable diplexer using two type tunable BPF and tunable matching circuit. Chi *et al.*[19] showed a tunable diplexer using tunable M-shaped resonators and tunable matching circuits. Feng *et al.*[20] showed a tunable diplexer using tunable open-loop resonators. Khater

Fig. 16 (a) Simulated results for the tunable diplexer in the case of adjusting DC voltage at the low-band side; (b) simulated results for a tunable diplexer in the case of adjusting DC voltage at the high-band side.

Fig. 18 (a) Measured results for the fabricated tunable diplexer in the case of adjusting DC voltage at the low-band side; (b) measured results for the fabricated tunable diplexer in the case of adjusting DC voltage at the high-band side.

Fig. 17 Photograph of the fabricated tunable diplexer.

et al.[21] showed a tunable diplexer with two BPFs and a bandstop filter, which made of substrate integrated waveguides (SIWs). Liu *et al.*[22] showed a tunable diplexer using $\lambda/2$ resonators with embedded varactors. Gao *et al.*[23] showed a tunable diplexer using tunable unique shaped resonators. Iqbal *et al.*[24] showed a tunable

diplexer using tunable TE_{101} and TE_{102} mode SIWs. Lu *et al.*[25] showed a tunable diplexer using the synchronously tunable-filter resonators (STRs) based on a $\lambda/4$ resonator. Guan *et al.*[26] showed a tunable diplexer using short-circuited stub-loaded resonators.

In Tables 3 and 4, the 3-dB absolute bandwidth (*ABW*) shows a constant *BW*, which is the band width between two frequency points below 3 dB from the maximum S_{21} characteristic. The values in the far-right column of Table 3 show whether a large *FTR* is obtained by maintaining a 3-dB *ABW* in each band. It shows this value is lower when the tunable diplexer has better performance. The isolation characteristic and 3-dB *ABW* deviation of the high-band for the proposed tuning diplexer show better performance than the others. Moreover, two BST-vars for each BPF and two DC voltage sources are used for tuning. That is the minimum number of varactors and DC voltage supplies.

Table 3 Benchmarking of tuning diplexers (1/2).

Ref.	Frequency Tuning Range (FTR) (GHz)				Center frequency of FTR (GHz)		Frequency width of FTR (GHz)		Fractional FTR (%)		3 dB ABW(MHz)		Deviation of 3 dB ABW(%)		Deviation of 3 dB ABW/Fractional FTR	
	low-band		High-band		low-band	High-band	low-band	High-band	low-band	High-band	low-band	High-band	low-band	High-band	low-band	High-band
[2]	15.72	19.44	20.51	21.31	17.58	20.91	1.72	0.8	9.78	3.83	ND	ND	ND	ND	ND	ND
[3]	2.26	2.8	2.62	3.3	2.53	2.96	0.54	0.68	21.3	23.0	177 ± 19	170 ± 20	10.7	11.8	0.5	0.5
[4]	1.9	2.7	2.5	3.4	2.3	2.95	0.8	0.9	34.8	30.5	139 (BW _{1dB}) ± 31	134 (BW _{1dB}) ± 29	22.3	21.6	0.6	0.7
[5]	0.538	0.935	1.057	1.691	0.7365	1.374	0.397	0.634	53.9	46.1	124 ± 46	154 ± 65	37.1	42.2	0.7	0.9
[6]	1.35	2.25	1.9	3	1.8	2.45	0.9	1.1	50.0	44.9	194 ± 8	194 ± 8	4.1	4.1	0.1	0.1
[7]	1.47	2.5	2.2	3.5	1.985	2.85	1.03	1.3	51.9	45.6	246 ± 22	247.5 ± 26.5	8.9	10.7	0.2	0.2
[16]	1.43	1.73	1.95	2.35	1.58	2.15	0.3	0.4	19.0	18.6	177 (BW _{1dB}) ± 48	131 (BW _{1dB}) ± 34	27.1	26.0	1.4	1.4
[17]	0.73	0.905	1.035	1.205	0.8175	1.12	0.175	0.17	21.4	15.2	62.5 ± 18	67.5 ± 10	28.8	14.8	1.3	1.0
[18]	1.425	1.71	1.85	2.27	1.745	1.8	0.65	0.74	37.2	41.1	75.2 (BW _{1dB}) ± 6.8	98.9 (BW _{1dB}) ± 10.1	9.0	10.2	0.2	0.2
[19]	0.94	1.21	1.51	1.91	1.075	1.71	0.27	0.4	25.1	23.4	75 ± 15	140 ± 20	20.0	14.3	0.8	0.6
[20]	0.88	1.05	1.66	1.87	0.965	1.765	0.17	0.21	17.6	11.9	59.2 ± 9.05	70.9 ± 9.5	15.3	13.4	0.9	1.1
[21]	0.7	1	0.75	1	0.85	0.875	0.3	0.25	35.3	28.6	17.5 ± 2.5	16.8 ± 8.3	14.3	49.4	0.4	1.7
[22]	1.05	1.3	1.31	1.62	1.175	1.465	0.25	0.31	21.3	21.2	50.1 ± 12.3	60.5 ± 17.3	24.6	28.6	1.2	1.4
[23]	0.72	1.05	1.22	1.72	0.885	1.47	0.33	0.5	37.3	34.0	57.3 (BW _{1dB}) ± 12	70.6 (BW _{1dB}) ± 12	20.9	17.0	0.6	0.5
[24]	10.07	11.5	13.7	14.54	10.785	14.12	1.43	0.84	13.3	5.95	475 ± 65	235 ± 15	13.7	6.4	1.0	1.1
[25]	1.05	1.35	1.3	1.6	1.2	1.45	0.3	0.3	25.0	20.7	133.5 ± 2.5	133.5 ± 2.5	1.9	1.9	0.1	0.1
[26]	0.87	0.92	1.05	1.14	0.895	1.095	0.05	0.09	5.59	8.22	35.5 ± 0.5	37.3 ± 2.8	1.4	7.5	0.3	0.9
This work	1.56	2.04	2.4	2.91	1.8	2.655	0.48	0.51	26.7	19.2	224 (BW _{1dB}) ± 57	231 (BW _{1dB}) ± 19	25.4	8.2	1.0	0.4

ND = no data was found in the paper

Table 4 Benchmarking of tuning diplexers (2/2).

Ref.	order		IL (dB)		RL (dB)		Isolation (dB)		Normalized by λ_g		Tuning element	A number of tuning elements
	low-band	High-band	low-band	High-band	low-band	High-band	low-band	High-band	x	y		
[2]	2	2	5.74–7.19	5.54–6.27	ND	ND	ND	ND	1.932	1.308	STO film	4
[3]	2	2	2.68–5.8	3.7–5.2	>7	>7	>40	>35	0.780	0.390	Si varactor	10
[4]	2	2	3.5–6.3	3.5–6.3	>7	>10	>25	>30	0.037	0.158	Si varactor	8
[5]	3	3	2.2–4.35	3–7.72	>15	>15	>44	>54	0.095	0.058	Si varactor	16
[6]	3	3	<3.3	<3.3	>11	>11	>38	>38	0.42	0.19	GsAs varactor	8
[7]	3	3	<2.5	2.5 to 4.3	>15	>13	>40	>32	ND	ND	GsAs varactor	6
[16]	3	3	2.0–2.5	4.8–6.6	>10	>10	>35	>35	0.435	0.708	Si varactor	7
[17]	2	2	1.5–3.2	1.6–3.5	>15	>15	>22	>22	0.113	0.21	GsAs varactor	6
[18]	3	3	5–6.43	7.7–6.6	>7.5	>10	>40	>40	0.121	0.266	Si varactor	9
[19]	3	3	1.7–2.7	2.0–2.9	>16	>12	>51	>51	0.11	0.12	Si varactor	15
[20]	2	2	1.4–7.02	3.42–6.72	>15	>20	>45	>45	0.32	0.48	Si varactor	4
[21]	2	2	2.8–3.7	1.8–2.2	>10	>7	>40	>40	ND	ND	piezo element	4
[22]	2	2	2.8–3.1	4.6–5.0	>13	>13	>35	>35	0.46	0.197	Si varactor	16
[23]	3	3	1.1–1.6	1.6–2	>30	>30	>30	>30	0.094	0.095	Si varactor	11
[24]	2	2	0.8–1.3	1.35–2.2	>16	>16	>55	>55	2.14	1.3	Si varactor	4
[25]	4	4	3.4–3.6	2.65–3	>15	>15	>36	>36	ND	ND	Si varactor	8
[26]	2	2	4–4.5	4.2–5.5	>12	>12	>45	>45	0.25	0.25	Si varactor	8
This work	2	2	2.4–2.85	2.54–4.37	>5.4	>7.5	>48	>39	0.22	0.26	BST varactor	4

ND = no data was found in the paper

5. Conclusion

A tunable diplexer composed of asymmetric hairpin resonators using four varactors with constant ABW and high isolation characteristics was realized. The proposed asymmetric hairpin resonator was designed along the frequency characteristics of Q_e and k . Second-order BPFs for the low- and high-band using the proposed resonators were configured and fabricated. Those BPFs were tuned to the center frequencies while almost maintaining a constant BW . Finally, a tunable diplexer using the proposed asymmetric hairpin resonators and the minimum number of BST varactors was configured and fabricated. It was found that the isolation characteristic and 3-dB ABW deviation of the high-band for the proposed tuning diplexer showed better performance than for the others.

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