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A Design of Varactor-Tuned Combline Bandpass Filter Using Coupling Varactor Diode

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Abstract

In this paper, a novel varactor-tuned combline bandpass filter is presented. The coupling varactor diode between line elements is introduced to control the passband bandwidth so that the passband bandwidth can be maintained almost constant within the tuning range. The equivalent circuit and design equations are derived, and the optimum design is discussed. A 1.7 GHz, two-pole bandpass filter with a bandwidth of 4.5 % was constructed. The absolute passband bandwidth was maintained almost constant within more than 0.4 octave tuning range.

Key words : Combline Bandpass Filter, Constant Passband Bandwidth, Tunable Bandpass Filter.

Ⅰ. Introduction

The varactor-tuned combline bandpass filter[1] is an attractive choice among several types of varactor-tuned RF tunable bandpass filters[1]~[4]. Using this filter, octave tuning can be achieved while retaining minimum degradation in passband performance[1],[5]~[7]. The passband bandwidth of this filter can also be maintained *approximately* constant independent of tuned frequency by selecting a properly chosen electrical length of transmission line segment. The filter reported in [1] has been tuned more than 0.4 octave tuning range with less than 12.5 % variations in absolute passband bandwidth. In [8], a varactor-tuned combline bandpass filter using step-impedance microstrip lines are considered to achieve constant filter response and bandwidth. Valuable discussions of the problem of obtaining nearly constant bandwidth in the tunable bandpass filter can also be found in literatures[9],[10]. However, previous results[1]~[10] show that the passband bandwidth of the tunable bandpass filter will inevitably vary as the filter is tuned. In general, a wider tuning range will cause greater passband bandwidth variation[4],[9]. In this paper, we will consider a novel varactor-tuned combline bandpass filter to achieve *almost* constant absolute passband bandwidth independent of tuned frequency[13]. Fig. 1 shows a novel varactor-tuned combline bandpass filter proposed in this paper. This filter has an additional coupling varactor diode between line elements so as to control the passband bandwidth. The coupling varactor diode is located near the short-circuited point. Since the magnetic coupling is dominant in the combline structure[9], an increase in the equivalent capacitance of the coupling varactor diode will result in a decrease in passband bandwidth. Therefore, using this structure, a narrowband filter can be easily realized. A properly chosen equivalent capacitance value and the position of the coupling varactor diode enable the passband bandwidth to be controlled so that the passband bandwidth could be maintained almost constant within the tuning range. It will be shown that more than 0.4 octave tuning range with almost constant absolute passband bandwidth can be achieved using a proposed filter. Design equations of the proposed structure will be derived, and experimental results will be presented.

Ⅱ. Theory and Design Equations

For narrow bandwidth applications, it has been shown that the coupling coefficient is the convenient design parameter. In this paper, an equivalent circuit for the circuit presented in Fig. 1 will be derived using a

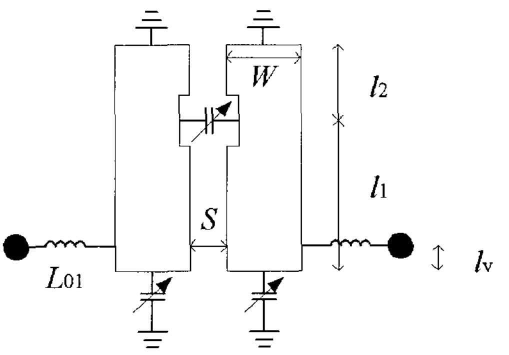

Fig. 1. A novel varactor-tuned combline bandpass filter using coupling varactor diode.

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similar method presented in [8]. Then, a closed form expression for the coupling coefficient will be derived.

2-1 Constant Bandwidth Requirement

To maintain constant passband bandwidth, the coupling coefficient, *k*, must vary inversely with the tuning frequency as expressed in the following equation[9]:

$$k_{j,j+1}\big|_{j=1ton-1}=\frac{J_{j,j+1}}{\sqrt{b_j b_{j+1}}}=\frac{W}{\sqrt{g_j g_{j+1}}}\propto\frac{1}{f_0} \tag{1}$$

where, *J*'s are the inverter values, *b*'s are the slope parameters of the resonators, *W* is the fractional bandwidth, *g*'s are the element values of the lowpass prototype filter, and f_0 denotes the center frequency of the tuned frequency.

2-2 Coupling Coefficient[8]

To calculate the coupling coefficient, the voltages and currents at each port are defined as shown in Fig. 2. The equivalent variable capacitance for the varactor diode positioned between line elements is represented by C_c. In this paper, this varactor diode will be referred to as a 'coupling varactor diode'. C_v represents the equivalent variable capacitance for the varactor diode positioned at the end of the line element to ground. In this paper, this varactor diode will be referred to as a 'tuning varactor diode'.

The relationship between the voltages and currents is [11], [12]:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}=\begin{bmatrix} Y_{b11} & Y_{b12} & Y_{b13} & Y_{b14} \\ Y_{b21} & Y_{b22} & Y_{b23} & Y_{b24} \\ Y_{b31} & Y_{b32} & Y_{b33} & Y_{b34} \\ Y_{b41} & Y_{b42} & Y_{b43} & Y_{b44} \end{bmatrix}\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \tag{2}$$

where,

$$Y_{b11}=Y_{b22}=Y_{b33}=Y_{b44}=-\frac{j}{2}\left(Y_o\cot\theta_{2o}+Y_e\cot\theta_{2e}\right),$$

$$Y_{b12}=Y_{b21}=Y_{b34}=Y_{b43}=-\frac{j}{2}\left(Y_o\cot\theta_{2o}-Y_e\cot\theta_{2e}\right),$$

$$Y_{b13}=Y_{b31}=Y_{b24}=Y_{b42}=-\frac{j}{2}\left(Y_o\csc\theta_{2o}+Y_e\csc\theta_{2e}\right),$$

$$Y_{b14}=Y_{b41}=Y_{b23}=Y_{b32}=-\frac{j}{2}\left(Y_o\csc\theta_{2o}-Y_e\csc\theta_{2e}\right),$$

Y_o, Y_e are the odd and even mode impedances of line elements, and θ_{2o}, θ_{2e} are the odd mode and even mode electrical lengths of line elements between coupling varactor diode and the open-circuit point of the line element(Fig. 2).

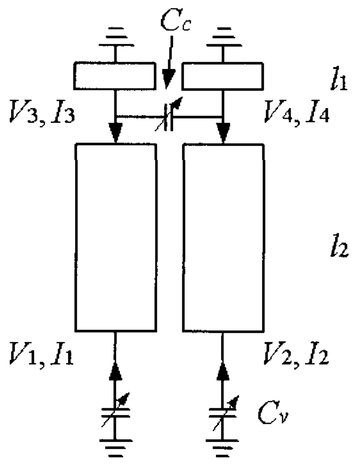

Fig. 2. Definition of the voltages and the currents at each port.

I_3, I_4, V_3 and V_4 will satisfy (3)

$$\begin{bmatrix} I_3 \\ I_4 \end{bmatrix}=-\begin{bmatrix} Y_{a11} & Y_{a12}+jwC_c \\ Y_{a21}+jwC_c & Y_{a22} \end{bmatrix}\begin{bmatrix} V_3 \\ V_4 \end{bmatrix} \tag{3}$$

where,

$$Y_{a11}=Y_{a22}=-\frac{j}{2}\left(Y_o\cot\theta_{1o}+Y_e\cot\theta_{1e}\right),$$

$$Y_{a12}=Y_{a21}=-\frac{j}{2}\left(Y_o\cot\theta_{1o}-Y_e\cot\theta_{1e}\right)$$

θ_{1o}, θ_{1e} are the odd and even mode electrical lengths of line elements between coupling varactor diode and the short-circuited point of the line element(Fig. 2).

Substitute (3) to (2) to obtain

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix}=\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \tag{4}$$

where,

$$\begin{aligned} Y_{11}=Y_{22}=&-\frac{j}{2}\Big(Y_o\cot\theta_{2o}+Y_e\cot\theta_{2e} \\ &-\frac{Y_e^2\csc^2\theta_{2e}}{Y_e\cot\theta_{1e}+Y_e\cot\theta_{2e}+wC_c}-\frac{Y_o^2\csc^2\theta_{2o}}{Y_o\cot\theta_{1o}+Y_o\cot\theta_{2o}-wC_c}\Big),\end{aligned}$$

$$\begin{aligned} Y_{12}=Y_{21}=&-\frac{j}{2}\Big(Y_o\cot\theta_{2o}-Y_e\cot\theta_{2e} \\ &+\frac{Y_e^2\csc^2\theta_{2e}}{Y_e\cot\theta_{1e}+Y_e\cot\theta_{2e}+wC_c}-\frac{Y_o^2\csc^2\theta_{2o}}{Y_o\cot\theta_{1o}+Y_o\cot\theta_{2o}-wC_c}\Big)\end{aligned}$$

The equivalent circuit of a symmetrical pair of resonators can be obtained from (4) such as shown in Fig. 3, where Y_1, and Y_2 are

$$Y_1=-j\frac{Y_e^2\cos\theta_e+wC_cY_e\sin\theta_{1e}\cos\theta_{2e}}{Y_e\sin\theta_e+wC_c\sin\theta_{1e}\sin\theta_{2e}} \tag{5}$$

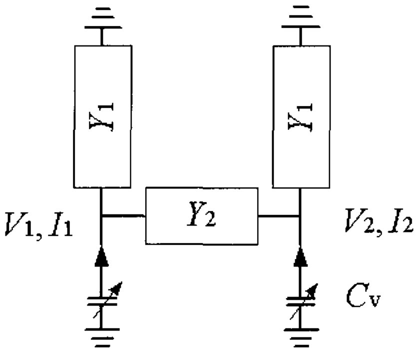

Fig. 3. Equivalent circuit for the circuit presented in Fig. 2.

$$Y_2 = -\frac{j}{2}\left(Y_o \frac{Y_o \cos\theta_o - wC_c \sin\theta_{1o} \cos\theta_{2o}}{Y_o \sin\theta_o - wC_c \sin\theta_{1o} \sin\theta_{2o}} - Y_e \frac{Y_e \cos\theta_e + wC_c \sin\theta_{1e} \cos\theta_{2e}}{Y_e \sin\theta_e + wC_c \sin\theta_{1e} \sin\theta_{2e}} \right) \tag{6}$$

where, $\theta_e = \theta_{1e} + \theta_{2e}$, and $\theta_e = \theta_{1o} + \theta_{2o}$.

The coupling coefficient, k, can be expressed as

$$k = \frac{|jY_2|}{b} \tag{7}$$

where, b is the slope parameter of the resonator which can be derived from (5) and is given as

$$b = \frac{1}{2} \frac{\theta_e Y_e^3 - wC_c Y_e^2 \sin^2\theta_{1e} + 2\theta_{2e} wC_c Y_e \sin\theta_{1e} (Y_e \cos\theta_{1e} + wC_c \sin\theta_{1e})}{(Y_e \sin\theta_e + wC_c \sin\theta_{1e} \sin\theta_{2e})^2} + \frac{wC_v}{2}.$$

For the filter realized in stripline, the even and odd mode phase velocities are same, and (4)~(7) can be simplified accordingly.

III. Design Considerations

The length of the line element of the varactor-tuned combline bandpass filter are closely related to the filter performance. The length of the line element should be as short as possible for the widest tuning range and a longer electrical length of line element will result in better overall quality factor[4]. If there is no coupling varactor diode between resonators, the length of the line element should be the optimum value to achieve the optimum performance in terms of constant filter response shape and bandwidth[1]. Therefore, trade-off in choosing the length of the line element exists. For the filter considered in this paper(Fig. 1), the passband bandwidth will be maintained almost constant by utilizing the coupling varactor diode. Therefore, the length of the line element could be chosen to achieve a wide tuning range and/or a minimum passband insertion loss while retaining constant filter response shape and bandwidth.

An exact resonance frequency can be derived from (5). However, to a good approximation, the resonance frequency can be expressed by (3) in [4] as the following equation

$$Y_{in} = j\left(wC_v - Y_e \cot\theta_e\right) = 0 \tag{8}$$

The resonance condition at f_{max}(the center frequency of the passband when the filter is tuned to the maximum frequency of the tuning range) and f_{min}(the center frequency of the passband when the filter is tuned to the minimum frequency of the tuning range) can be expressed as the following two equations

$$2\pi f_{max} C_{min} = Y_e \cot\theta_{max} \tag{9}$$

$$2\pi f_{min} C_{max} = Y_e \cot\theta_{min} \tag{10}$$

where, C_{max} is the equivalent capacitance value of the tuning varactor diode when the filter is tuned to f_{min}, C_{min} is the equivalent capacitance value of the tuning varactor diode when the filter is tuned to f_{max}, θ_{max} is the electrical length of the line element at f_{max}, and θ_{min} is the electrical length of the line element at f_{min}($\theta_{min} = \theta_1 + \theta_2$ at f_{min}, see Fig. 2).

Divide equation (9) to equation (10) to obtain

$$\frac{f_{max}}{f_{min}} \frac{C_{min}}{C_{max}} = \frac{\alpha'}{C_{ratio}} = \frac{\tan\theta_{min}}{\tan\theta_{max}} = \frac{\tan\theta_{min}}{\tan\alpha'\theta_{min}} \tag{11}$$

where, $\alpha' = \alpha + 1 = \frac{f_{max}}{f_{min}}$, and $C_{ratio} = \frac{C_{max}}{C_{min}}$ is the capacitance ratio of the tuning varactor diode.

Therefore, the tuning range, a, can be expressed by the following equation:

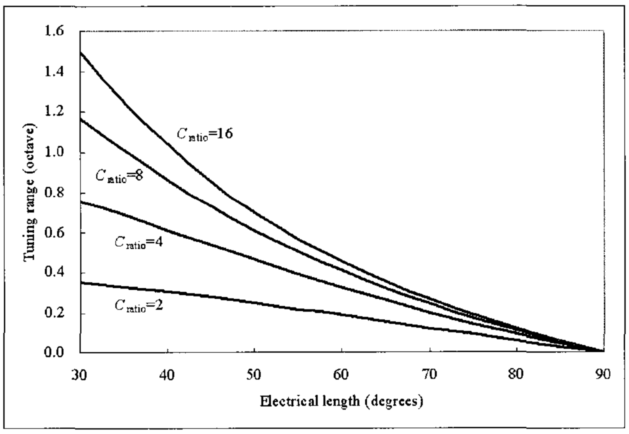

Fig. 4. Theoretical tuning range as functions of θ_{min}(the electrical length of the line element at the center of the passband when the filter is tuned to the minimum frequency of the tuning range, $\theta_{min} = \theta_1 + \theta_2$ at f_{min}, see Fig. 2) and C_{ratio}(the capacitance ratio of the tuning varactor diode).

$$\alpha = C_{\text{ratio}} \frac{\tan\theta_{\min}}{\tan(\alpha+1)\theta_{\min}} - 1 \tag{12}$$

Fig. 4 shows the resulting tuning range, α, as functions of θ_{min} and C_{ratio}. For example, if electrical length of the line element is 37 degrees at f_{min} and the capacitance ratio of the tuning varactor diode is 2.5, then approximately 0.43 octave tuning is possible. As the length of line element becomes electrically longer, the overall quality factor becomes increased [4] as referred to before. Therefore, the optimum electrical length of line element would be a length that provides no more than required tuning range. This length can be determined using (12) and Fig. 4.

In this paper, design parameter values such as the even and odd mode characteristics impedances of coupled microstrip lines, the position as well as the required equivalent capacitance of the coupling varactor diode will be determined for a specified design as presented in the following section.

Ⅳ. Experimental Results

A varactor-tuned combline bandpass filter using the proposed structure has been designed and tested according to the following specifications:

Tuning range: 1.4 GHz~2.0 GHz(about 0.43 octave)
Number of poles: 2
Passband bandwidth: 75 MHz(fractional bandwidth =about 4.4 % at 1.7 GHz)
Type: 0.01 dB Chebyshev

The varactor diode used in this design is 1sv277[1]. The measured capacitance of this varactor diode at -8 V voltages is about 1.5 pF with capacitance ratio of 2.5 around the tuning range. Microstrip structure using Taconic TLC 32(ε_r=3.2, h=0.8 mm)[2] substrate is used. By utilizing Fig. 4, the even mode electrical length of the line element, θ_e, is chosen as 37 degrees at f_{min}(1.4 GHz) to provide 0.43 octave tuning range with minimum passband insertion loss [4]. This even mode electrical length corresponds to 53 degrees at f_{max}(2 GHz). The same varactor diode in a back-to-back configuration has been used as the coupling varactor diode. In order to achieve minimum passband insertion loss, the equivalent capacitance of the coupling varactor diode should be as small as possible within the tuning range. The equivalent capacitance of coupling varactor diode at −6 V voltages in a back-to-back configuration is about 1 pF. This bias voltage is chosen for the bias of the coupling varactor diode at f_{max}. A lumped inductor has been used for input and output coupling networks. The position and value of a lumped inductor have been determined according to the method presented in [8], and designed values can be found in Table 1. The even mode impedance, Z_e=1/Y_e, is closely related to the resonance frequency. Since the existence of the coupling varactor diode will slightly shift the resonance frequency, the position and equivalent capacitance value of C_c would have negligible effect on determining the even mode impedance that satisfies the resonance condition. If this assumption is true, then the even mode impedance will satisfy (13)[9]

$$Y_e \cot\theta_e = kb_{1r} + \frac{G_A^2 B_{01}}{G_A^2 + B_{01}^2} + wC_v \tag{13}$$

where, $k = \frac{W}{\sqrt{g_1 g_2}}$, $b_{1r} = \frac{Y_e}{2}\frac{\theta_e}{\sin^2\theta_e} + \frac{wC_v}{2}$, $B_{01} = -\sqrt{\frac{J_{01}^2 G_A^2}{G_A^2 - J_{01}^2}}$,

$J_{01} = \sqrt{\frac{b_1 G_A}{Q_e}}$, $Q_e = \frac{g_0 g_1}{W}$ [9], $b_1 = \frac{Y_e}{2}\frac{\theta_e - \theta_{ve}}{\sin^2(\theta_e - \theta_{ve})}$ $+ \frac{Y_e}{2}\frac{wC_v Y_e + (wC_v)^2\theta_{ve} + Y_e^2\theta_{ve}}{(Y_e\cos\theta_{ve} - wC_v\sin\theta_{ve})^2}$ [8], and θ_{ve} is the even mode electrical length between the open-circuited point of the line element and the point where input/output coupling inductor is positioned [8].

Note that, in (13), all values except the even mode admittance have been given. Therefore, the even mode impedance that satisfies (13) can be solved at f_{max}, and the resultant value is about 53.5 Ω.

The odd mode impedance can now be obtained by equating (1) and (7) at f_{max}. Fig. 5 shows the odd mode impedance to obtain 75 MHz passband bandwidths at f_{max} as functions of θ_{1max}(θ_1 at f_{max}) and the ratio between the odd and even mode phase velocities $\zeta = \sqrt{\varepsilon_{od}/\varepsilon_{even}}$, where ε_{odd} is the odd mode permittivity and ε_{even} is the even mode permittivity. For example, if the coupling varactor diode is located at 14 degrees(at f_{max}) from the short-circuited point and the ratio between the odd and even mode phase velocities is 0.93, then the odd mode impedance should be about 43 Ω to assure 75 MHz passband bandwidths at f_{max}.

Table 1. Design values of varactor-tuned combline bandpass filter using coupling varactor diode. The geometrical parameters are illustrated in Fig. 1.

W	2 mm	S	0.9 mm	l_l	10 mm
l_2	3.5 mm	l_v	1 mm	L_{01}	14 nH

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[1] Toshiba Corporation.

[2] Taconic.

The equivalent capacitance of the coupling varactor diode, C_c, will be varied to control the passband bandwidth so that the passband bandwidth could be maintained almost constant within tuning range. The required capacitance ratio of the C_c to maintain constant passband bandwidth can be obtained by equating (1) and (7) at f_{min}. Fig. 6 shows the resulting C_c to obtain 75 MHz passband bandwidths at f_{min} as functions of θ_{1max} and ζ with selecting odd impedances as presented in Fig. 5. For example, if the coupling varactor diode is located at 14 degrees(at f_{max}) from the short-circuited point and the ratio between the odd and even mode phase velocities is 0.93, then the equivalent capacitance of the coupling varactor diode should be about 1.3 pF to assure 75 MHz passband bandwidths at f_{min}. In some cases, the required capacitance ratio of the C_c can be slightly larger than calculated values as described above, since required capacitance value of the C_c can be largest at some frequency between f_{min} and f_{max}.

From Fig. 5 and Fig. 6, the electrical length between the position where the coupling varactor diode is positioned and the short-circuited point, θ_1, is chosen as 14 degrees(at f_{max}) since this choice will result in reasonable design parameter values. Conversion from electrical parameters to physical values is performed using the commercially available software, such as LineCalc[3]. The design values are summarized in Table 1. In this case, the ratio between the odd and even mode phase velocities, ζ, is about 0.93. Fig. 7 shows the calculated coupling coefficient according to (7) along with desired value based on (1). It can be found that the passband bandwidth can be maintained almost constant by changing the equivalent capacitance of the coupling varactor diode from 1 pF to 1.3 pF. The simulated as well as the experimental performance of this filter are presented in Fig. 8. Simulations were performed using commercially available software, such as Momentum[4].

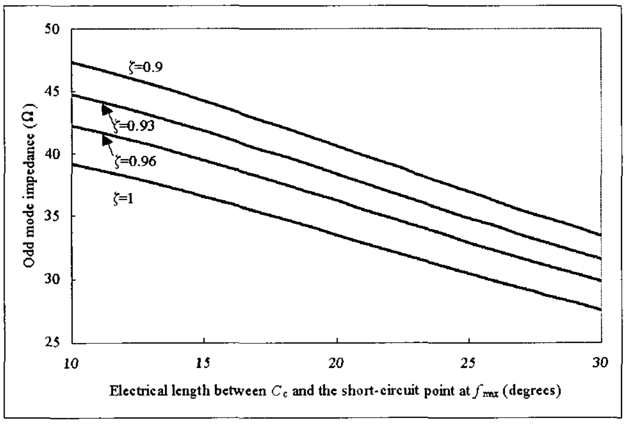

Fig. 5. The theoretical odd mode impedance to obtain 75 MHz passband bandwidths at f_{max} as functions of θ_{1max}(the electrical length between the position where coupling varactor diode is positioned and the short-circuited point at f_{max}) and ζ (the ratio between the odd and even mode phase velocities) with θ_e=53 degrees, Z_{even}=53.5 Ω, C_v=1.5 pF, and C_c=1 pF at f_{max}=2 GHz.

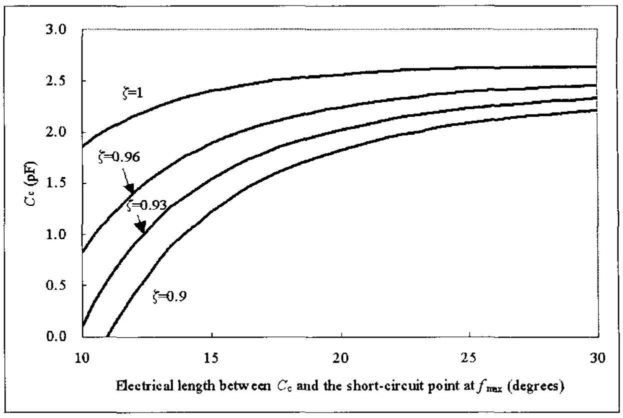

Fig. 6. The theoretical equivalent capacitance of the coupling varactor diode to obtain 75 MHz passband bandwidths at f_{min} as functions of θ_{1max} (the electrical length between the position where coupling varactor diode is positioned and the shorted-circuit point at f_{max}) and ζ (the ratio between the odd and even mode phase velocities) with θ_e=37 degrees, Z_{even}=53.5 W, and C_v=3.3 pF at f_{min}=1.4 GHz. The odd mode impedance is selected as presented in Fig. 5.

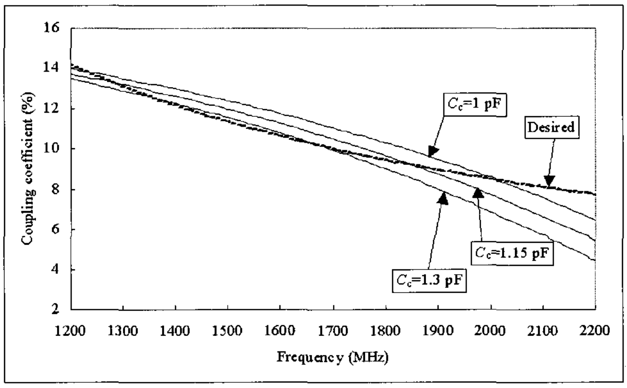

Fig. 7. Frequency variation of coupling coefficients as a function of the equivalent capacitance of the coupling varactor diode(C_c): The thin solid lines are calculated values according to (7) and the thick dashed line is desired ones according to (1).

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[3] Agilent Technologies.

[4] Agilent Technologies.

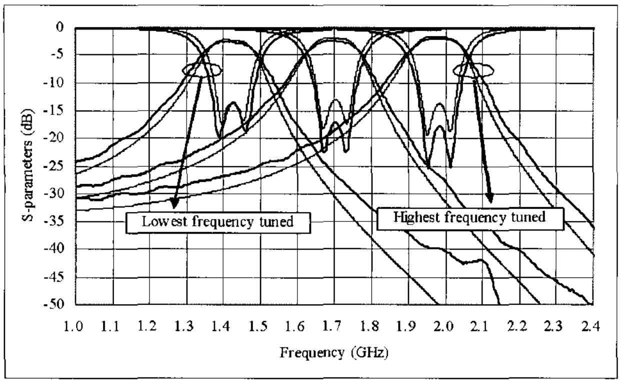

Fig. 8. Simulated and experimental results(S_{11}, S_{21}): The thick lines are measured values and the thin lines are simulated ones. The 3 dB passband bandwidth is almost constant within more than 0.4 octave tuning range at 1.7 GHz.

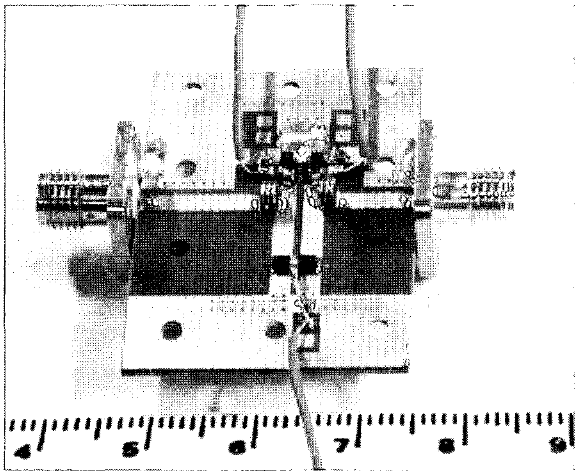

Fig. 9. Photograph of experimental 2-pole varactor-tuned combline bandpass filter using the coupling varactor diode.

Simulated and experimental results show that the 3 dB passband bandwidth is maintained almost constant within more than 0.4 octave tuning range at 1.7 GHz. Fig. 9 shows the photograph of the designed tunable bandpass filter.

In Fig. 9, one can find that the passband insertion loss is slight higher when the filter is tuned to the lowest frequency within the tuning range compared with its passband insertion loss when the filter is tuned to the highest frequency within the tuning range. This is due to the inverse-proportional property of the Q factor in this type of resonators.

V. Conclusion

In this paper, a novel varactor-tuned combline bandpass filter is presented. The coupling varactor diode is introduced near the short-circuited point to control the passband bandwidth so that the absolute passband bandwidth can be maintained almost constant within the tuning range. The equivalent circuit and design equations are derived, and the optimum design is discussed. The even and odd mode impedance, and the position as well as the required equivalent capacitance ratio of the coupling varactor diode have been determined for the optimum performance. Experimental results at 1.7 GHz show that the passband bandwidth is almost constant within more than 0.4 octave tuning range.

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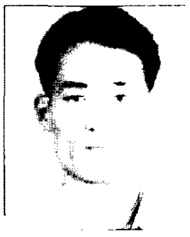

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