Tunable bandpass filter based on capacitor-loaded metamaterial lines

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A bandpass filter is constructed by loading a left-handed metamaterial transmission line with an additional shunt capacitor. The shunt capacitor provides more freedom to control the passband characteristics of the resulting metamaterial line. A bandpass filter is designed with a centre frequency that is tunable from 0.45 to 0.65 GHz.

Introduction: Traditionally, the metamaterial (MTM) lines have been synthesised by periodically loading a host transmission line (TL) with series capacitors and shunt inductors [1]. They support a backward-wave fundamental harmonic and hence a negative index of refraction when arranged in the form of two-dimensional or three-dimensional grids [1]. These lines have been employed to build compact wideband phase shifters, filters and other electromagnetic devices [2]. In this Letter, we propose a metamaterial-based bandpass filter that is obtained by loading the traditional MTM lines with an additional shunt capacitor. This extra capacitive loading provides more freedom in controlling the cutoff frequency of the fundamental mode and the subsequent stopband. Furthermore, varactors can be employed to tune the amplitude and phase response of the resulting bandpass filter.

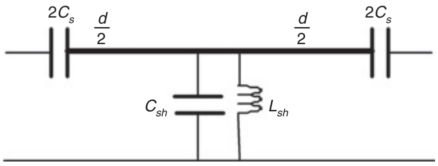

Fig. 1 *Unit cell of capacitor-loaded MTM line*

Filter design: Applying the Bloch-Floquet theorem on the unit cell of Fig. 1, the dispersion equation of the capacitor-loaded MTM line is given by [3]:

$$\cosh kd = \cos \beta d\left[1+\frac{YZ}{4}\right]+\frac{j}{2}\sin \beta d[ZY_o+YZ_o]+\frac{YZ}{4} \tag{1}$$

where k is the Bloch propagation constant of the periodic structure. β and Z_o ($=1/Y_o$), respectively, are the intrinsic phase constant and the characteristic impedance of the unloaded line. Y and Z are the series admittance and shunt impedance of the loading elements. Consider the Brillouin diagram of a capacitor-loaded MTM line (Fig. 2), obtained from (1). The three frequencies (f_o, f_L, f_H) shown on the dispersion diagram are given by [4]:

$$\omega_o = \frac{1}{2\sqrt{L_{sh}C_s}},\ \omega_L = \frac{1}{\sqrt{L_{sh}C'}},\ \omega_H = \frac{1}{\sqrt{L_o d C_s}} \tag{2}$$

where $C' = C_o d + C_{sh}$. As shown in the Figure, there is no transmission below the Bragg frequency f_o because of the high impedance offered by the series capacitance C_s. The S_{21} magnitude shows that the transmission takes place within the fundamental band $f_o < f < f_L$ in which the phase shift per unit cell decreases as the frequency increases (backward-wave propagation). The fundamental band is followed by a bandgap ($f_L < f < f_H$) and another passband in which the transmission takes place as a forward-wave. It can be readily deduced from (2) that by varying the shunt loading capacitance C_{sh}, the cutoff frequency of the fundamental band can be changed and hence the bandwidth of the associated passband can be controlled. This phenomenon is also depicted in Fig. 2 where the passband widens as the shunt capacitor is lowered from 12 to 8.8 pF. In the absence of the extra capacitor, the length of the host transmission line segment 'd' would have to be altered, which is practically not possible in the compact structures. The design equations are obtained from the approximate phase shift equation (when βd and $kd \ll 1$) and the Bloch impedance relation:

$$\theta^2 = (kd)^2 = \frac{1-\omega^2/\omega_L^2}{\omega^2 L_{sh}C_s},\quad Z_B^2 = \frac{L_{sh}}{C_s}\frac{1-\omega^2/\omega_H^2}{1-\omega^2/\omega_L^2} \tag{3}$$

Solving the above two equations for an N-stage bandpass filter with arbitrary phase and impedance yields:

$$C_s = \frac{N}{\theta Z_B \omega_{centre}}\sqrt{1-\frac{\omega_{centre}^2}{\omega_H^2}},\ L_{sh} = \frac{1}{4C_s\omega_o^2} \tag{4}$$

where $\omega_{centre} = (\omega_o + \omega_L)/2$. The rest of the design parameters are given obtained from (2) and (4):

$$d = \frac{1}{L_o C_s \omega_H^2},\ C' = \frac{1}{L_{sh}\omega_L^2},\ \text{and } C_{sh} = C' - C_o d \tag{5}$$

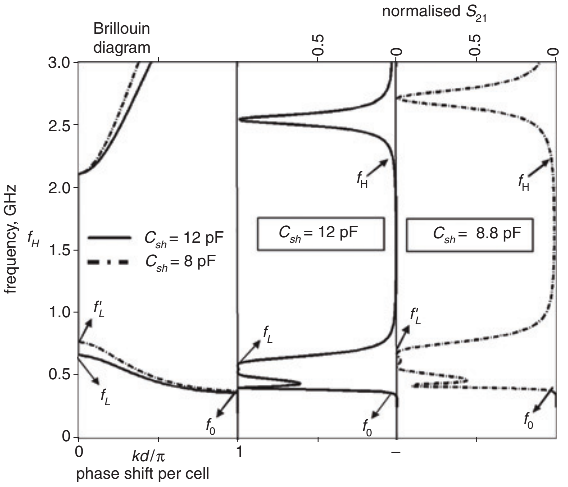

Fig. 2 *Brillouin diagrams and associated transmission coefficients of proposed periodic structure with $C_{sh} = 12$ pF and 8.8 pF (other parameters: $C_s = 6.8$ pF, $L_{sh} = 4.7$ nH, $d = 0.5$ cm)*

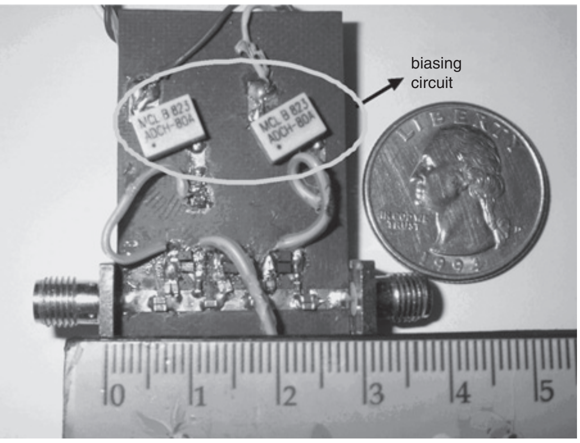

Fig. 3 *Fabricated bandpass filter based on capacitor-loaded MTM lines (biasing circuit also shown)*

Practical circuit: A practical bandpass filter is designed with a three-cell ($N = 3$) capacitor-loaded MTM line having a Bloch impedance of 50 Ω and a total phase shift of 135° at $f_{centre} = 0.6$ GHz with the cutoff frequencies $f_O = 0.45$ GHz and $f_H = 2$ GHz. The design equations (4) and (5) give $L_{sh} = 4.7$ nH, $C_s = 6.8$ pF, $C_{sh} = 10$ pF and $d = 0.5$ cm. The fabricated filter, depicted in Fig. 3, is implemented on a Rogers RT/Duroid 5880 substrate ($\epsilon_r = 2.2$, $h = 0.7874$ mm). To provide a DC block to the shunt inductor and to obtain a reasonable tuning range, the single shunt capacitor is replaced by a combination of a 24 pF fixed capacitor in series with two parallel SMTD3006 (Aeroflex-Metallics) varactors that have a capacitance of 7–16 pF with 15–1.5 V bias. Hence the tunable range of the shunt capacitor (C_{sh}) is 8.84–14 pF. The simulation and experimental results for $C_{sh} = 9$ pF (Fig. 4) are obtained from Agilent's ADS and an Anritsu 37369C vector network analyser. The results show close resemblance in terms of cutoff frequencies and overall bandpass shape. However, there is a transmission loss of about 2.5 dB that mainly comes from the lumped components. A superposition of S-parameters for the whole varactor range, depicted in Fig. 5, shows that the centre frequency of the bandpass filter can be tuned from about 0.45 to 0.65 GHz, which can be increased by using the appropriate varactor model. The transmission coefficient and the return losses in all cases are better than −3 and 12 dB, respectively. The fabricated circuit has a size of about 3 × 0.5 cm, excluding the biasing network. Thus the length is about $1/17$ of the free-space wavelength at the tunable-range centre.

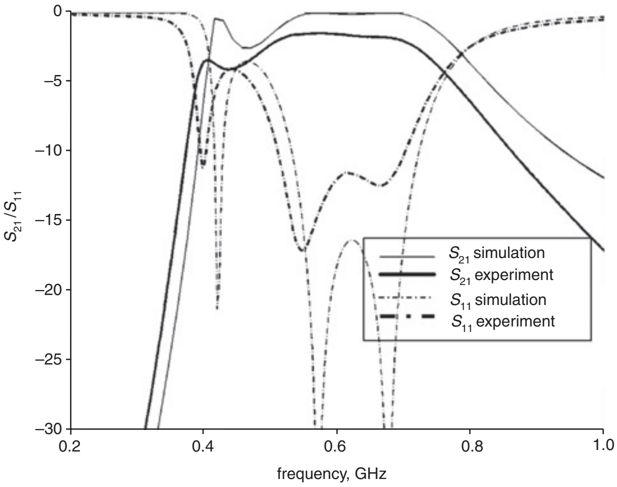

Fig. 4 *Simulation and experimental results for shunt capacitive loading of 9 pF (14 V bias on varactor)*

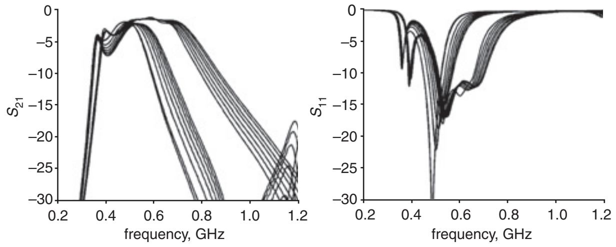

Fig. 5 *Superposition of S-parameters for complete varactor tunable range, i.e. 1 to 15 V*

Conclusion: A compact tunable bandpass filter based on the varactor-loaded metamaterial line is proposed and practically implemented. A tunable range of 200 MHz with a centre frequency of 0.55 MHz is obtained. Simulation and experiment show good agreement.

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