Reconfigurable Delay Lines with Split-Ring Resonators

Radovan Bojanic[1], Branka Jokanovic[1] and Vojislav Milosevic[1]

Abstract – **In this paper we proposed anovel multiband delay line which consists of two types of split-ring resonators: the broadiside coupled and the single split-ring resonator. Proposeddelay line exhibits two left-handed bands that can be shifted by twisting the split rings for certain angle or by changing their lengths. This delay line is suitable for design of multiband frequency scanning antennas since can provide phase shift of 70 degrees per 100MHz of frequency shift. Reconfigurability of the proposed delay line is demonstrated with two novel configurations obtained by switching ON/OFF a PIN diode placed at the upper split-ring resonator.**

Keywords – **Delay line, Split-ring resonator, Group delay, Effective parameters, Left-handed metamaterials.**

I. INTRODUCTION

Reconfigurable, multi band devices play an important role in modern wireless communications and sensors. Metamaterialsare found to be very promising for application in multi band devices, due to their controllable nonlinear dispersion which provides arbitrary, non-harmonic related choice of operating frequencies.

Here we investigate different spatial arrangements of split-ring resonators (SRRs) obtained by rotating the individual split-rings, which can be done electronically.It was shown that twisting the angle between SRRs significantly affects electromagnetic properties of the structure due to different mechanism of electrical and magnetic interactions that arise from different spatial arrangements.

Any metamaterialwhose properties depend on its three-dimensional structures is called stereometamaterial. It was firstly proposed by N. Liu et al. [1] in nanophotonicsin analogy to stereoisomers in chemistry.Nontrivial magnetic interaction makes stereometamaterials more versatile than stereoisomers in chemistry, where generally only electric interactions are taken into account.

In our previous work [2], [3] we studied the properties of two pairs of identical broadside coupled SRRs which are twisted at angles 0, 90 and 180 degrees. It was found that both *S*-parameters and effective electromagnetic parameters are considerable changed, while the shift in resonant frequency of 66% can be obtained. Possibility of moving position of the slit in SRRs electronically, that mimics the mutual rotation between SRRs, provides by no means the additional degree of freedom in the design of reconfigurable devices.

In this paper we investigate the structure consisting of two different types of SRRs that are edge coupled with microstrip line: abroadside coupled SRRsand a single SRR. Since these two types of SRRs have different resonant frequencies andthe effective parameters, combining them in a delay line gives a multiband response with two left-handed (LH) bands.

In order to obtain the resonant frequencies in a certain frequency range, the single SRR can be designed withdifferent length, shape and angle in respect to broadside one which is considered fixed in this investigation.

The aim of this work is to design multiband delay lines with as greater as possible group delay for application in frequency scanning antenna arrays.

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II. EFFECTIVE ELECTROMAGNETIC PARAMETERS

Left-handed metamaterials represent one particular case of metamaterials that have negative refractive index. When saying that, we consider that the real part is negative, because it figures directly in expression for phase coefficient, and hence affects group index of refraction and group delay, since complex propagation coefficient is defined as:

$$\gamma = jn\frac{\omega}{c}\ ;\ \gamma = \alpha + j\beta\ , \tag{1}$$

whereω is angular frequency, c velocity of light in vacuum, and n index of refraction for which applies:

$$n = n' - jn''. \tag{2}$$

This way we obtain direct relation between phase coefficient β and real part of refraction index n':

$$\beta = \frac{2\pi}{\lambda_g} = \frac{2\pi f}{v_f} = \frac{\omega}{c}n'\ , \tag{3}$$

wherev_f represents phase velocity of wave propagating through equiphase medium.

Based on (3) we conclude that for knowing the basic parameters which define a delay line, that being the group index of refraction and group delay, it is necessary to know the index of refraction, and relations which give clearer picture about are the following:

$$n_g = \frac{c}{v_g} = \frac{c}{\frac{d\omega}{dk}} = c\frac{d(\frac{\omega\cdot n}{c})}{d\omega} = n + \omega\frac{dn}{d\omega}, \tag{4}$$

$$\tau_g = -\frac{d\phi(\omega)}{d\omega}, \tag{5}$$

wheren_g is group index of refraction, v_g group velocity, τ_g group delay, $\phi(\omega)$ phase of S_{21} parameter of signal which is transmitting through the given structure. It is important to state that between relations (4) and (5) existsthe linear dependence when dispersion is small.

Now the question which springs to mind is how to determine index of refraction. This is explained in detail in [4] and [5], so we will cover just basic steps. Namely, to determine index of refraction we need propagation coefficient γ, which is observable from (1), and to fully determine particular structure we also need characteristic impedance Z_{eff}, from which we determine effective equivalent parameters ε_{eff} and μ_{eff}. Complex propagation coefficient we obtain the following way:

$$\gamma = \pm\frac{1}{L}cosh^{-1}\frac{1-S_{11}^2+S_{21}^2}{2S_{21}} = \pm j\frac{\omega}{c}n\,, \tag{6}$$

where the sign is chosen based on condition $n'' > 0$, which tells us that a structure is passive. Formula for calculating characteristic impedance is:

$$Z_{eff} = \sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}} = \frac{1+\Gamma}{1-\Gamma}\cdot\frac{Z^{TL}}{Z_a^{TL}}, \tag{7}$$

where Z^{TL} and Z_a^{TL} are the characteristic impedances of microstrip line and the air-filled microstrip line, and Γ is reflection coefficient on transition from line to structure:

$$\Gamma = \frac{Z^M - Z^{TL}}{Z^M + Z^{TL}}, \tag{8}$$

where Z^M is characteristic impedance of the analyzed equivalent microstrip structure.

At last, final formula we need to calculate ε_{eff} and μ_{eff} is their direct dependence from index of refraction:

$$n = \sqrt{\mu_{eff}\varepsilon_{eff}}\,, \tag{9}$$

and from equations (7) and (9) follows that:

$$\mu_{eff} = Z_{eff}\cdot n\,;\ \varepsilon_{eff} = \frac{n}{Z_{eff}}. \tag{10}$$

The assumption used above is that structure is symmetric, which is not always the case. For non-symmetric structure, averaging of S parameters is used:

$$\overline{S_{11}} = \sqrt{S_{11}S_{22}}. \tag{11}$$

III. Structure Analysis

We proposed the basic configurationof multiband delay line which is realized on two-layer substrate (Fig. 1.).It consists of broadside coupled SRRs twisted by 90 degrees and a single SRR, both coupled to microstrip line at the opposite sides.The vertical via is placed in the middle between split-ring resonators and short-circuited microstrip lint to ground. All relevant dimensions of the structure are given in Fig. 2.

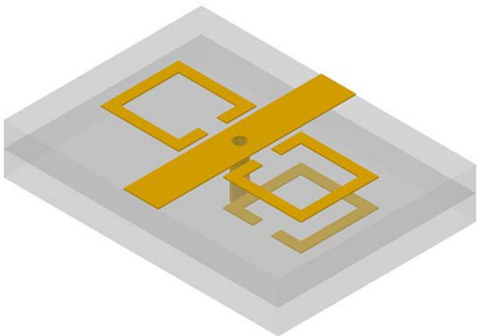


Fig. 1.Layout of multiband delay line (basic configuration). The upper substrate (dark gray) has ε_{r1}=10.2 and thickness h_1=0.635mm and lower substrate (light gray) has ε_{r2}=2.2 and thickness h_2=1.574mm

Broadside coupled SRRs twisted by 90 degrees are chosen as a building block for delay line, since our previous investigation [5] discovered that such arrangement of SRRs exhibited the greatest group index of refraction and group delay. In this application we use only one pair of broadside coupled resonators instead of two pairs [5], that gives a narrower left-handed band as well as the range with enhanced group delay.

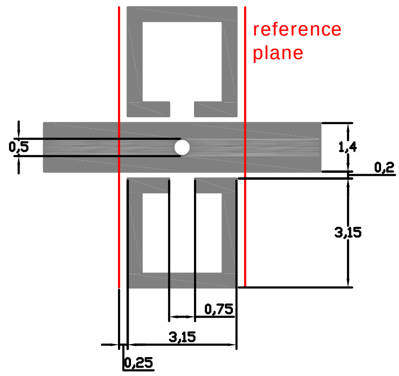


Fig. 2. Relevant dimensions of the basic delay line in mm

In order to show how the main building parts of a delay line influenceits overall characteristics: the single SRR and broadside coupled SRRs are simulated and compared in Figs. 3.-4.The real part of index of refraction and S_{21} are given in Fig. 3.while the group delay and imaginary part of index of refraction are shown in Fig. 4. It can be seen that both resonators exhibitthe negative refractive index, but in different frequency bands and also three very pronounced peaks in characteristic of group delay (additional peak is due to RH band). Combining these two resonators in a proposed delay line (Fig. 1) their responses are simply added giving two left-handed and one right-handed bands.Comparison between twobroadside coupled resonatorstwisted by 90 degrees [4], [5] and the proposed delay line is shown in Fig. 5. It can be seen that broadside coupled resonators have only one LH band, while delay line shows two LH bands, the first of which comes from a single broadside coupled SRRs, while the other one is due to resonance of a single SRR.

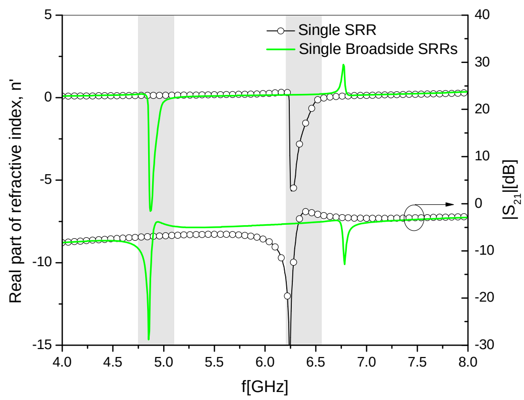


Fig. 3. Real part of index of refraction simulated for the individual building blocks of multiband delay line (Fig. 1.)LH bands are marked with rectangular bars

Position of the second LH band can be moved up and down changing the dimensions and orientation of a single SRRas it is shown in Fig. 7. In that delay line we have used an elongated single SRR rotated by 180 degrees whose length is 30 or 50 percent longer than in a basic delay line.

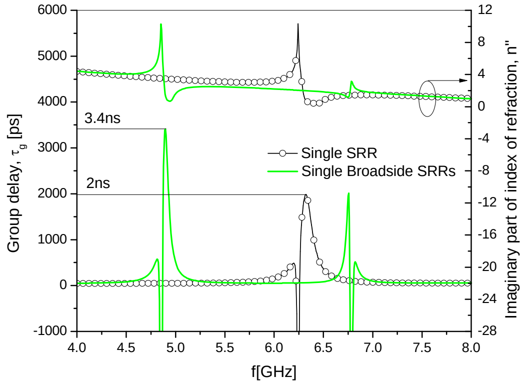


Fig. 4.Group delay and imaginary part of index of refraction simulated for the individual building blocks of multiband delay line

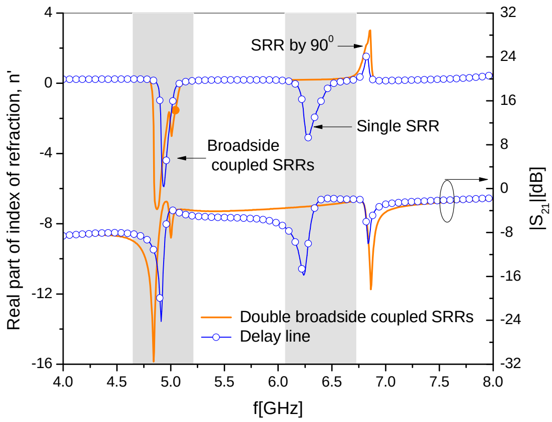


Fig. 5.Real part of index of refraction and S_{21} for broadside coupled SRRs placed symmetrically in respect to microstrip line (double broadside) and a proposed delay line. The origin of each resonance is indicated in diagram

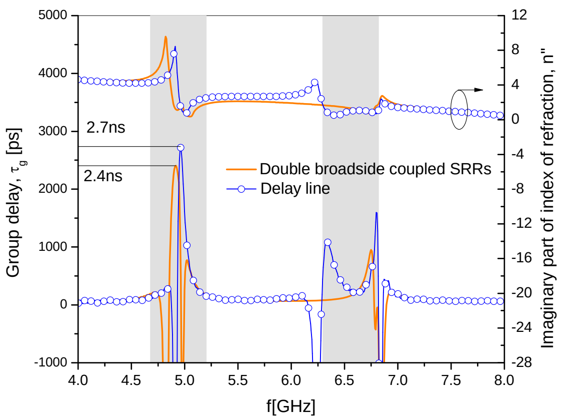


Fig. 6.Group delay and imaginary part of index of refraction (losses) for broadside coupled SRRs placed symmetrically in respect to microstrip line (double broadside) and a proposed delay line

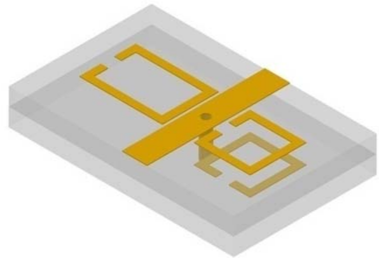


Fig. 7. Layout of the delay line with elongated single SRR. Its length is 50 percent longer than the broadside coupled SRRs.

Multiband response S_{21}, index of refraction and group delay of an elongated delay line(Fig. 7.)are shown in Fig. 8. and compared with the responsesof delay line whose single SRR has a length 30 percent longer than broadside coupled SRRs.

Rectangular bars denote the frequency ranges with negative index of refraction. The first and the third bands are unchanged if the length of a single SRR is changed, since they are caused by broadside coupled SRRs that are the same for both cases. It is shown that the second band can be shifted to lower and upper frequencies depending of the length of the single SRR.

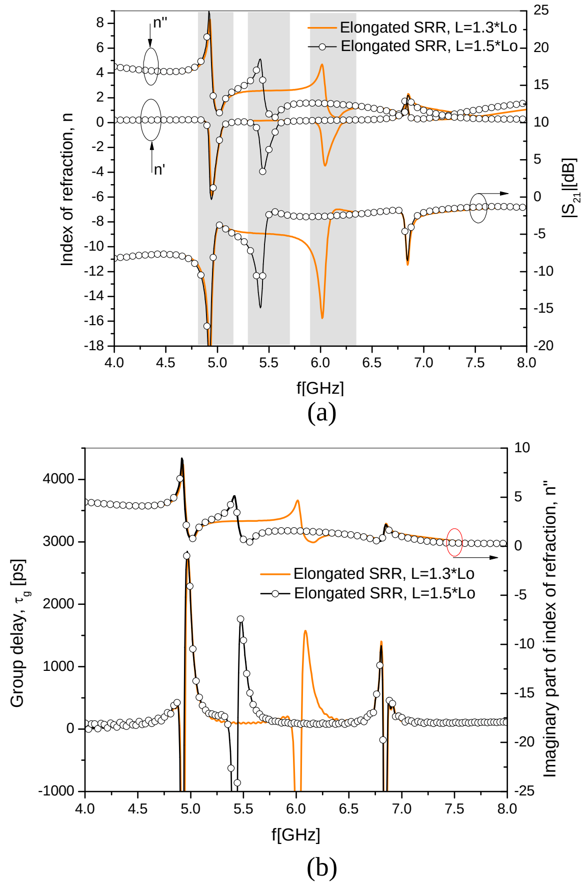
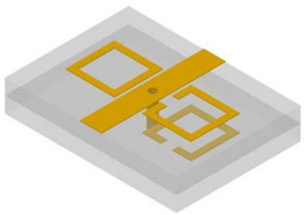


Fig. 8. Simulated results for the two lengths of elongatedsingle SRR: (a) S_{21} and index of refraction, n and (b) group delay, τg and imaginary part of refractive index (losses)

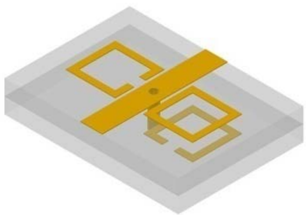
IV. Reconfigurability

It should be noted that rotation of SRRs presents nothing more than changing the gap position, so it is possible to realize it electronically using PIN diodes, which would open or close certain gaps. This approach would permit creation of electronically reconfigurable metamaterials, which electromagnetic properties could be changed in real-time and adjusted to momentary needs.

To demonstrate reconfigurability of proposed multiband delay line we simulated two simple modificationsof the basic delay line: (a) with the single SRR closed and (b) with the upper broadside coupled SRR closed. Electronic reconfigurability of the structure can be accomplished using PIN diodes placed at the gap of the upper SRRs. Switching the biasof the diode ON or OFF it is possible to change the operating regime of the delay line. Fig. 9 shows the layout of two modified delay lines.



(a) thesingle SRR closed



(b) the upper broadside SRR closed

Fig. 9.Layout of two simple modifications of the proposed delay line

Instead of closing SRR, the same electromagnetic response can be obtained with double-cut SRR, for instance by placing the additional gap at the opposite side ofthe existing one. In that case, PIN diode should be switched ON during the regular operation, while in the case of the closedSRR,the diode should be in the ON state only when changing the basic mode of operation, that seems more convenient.

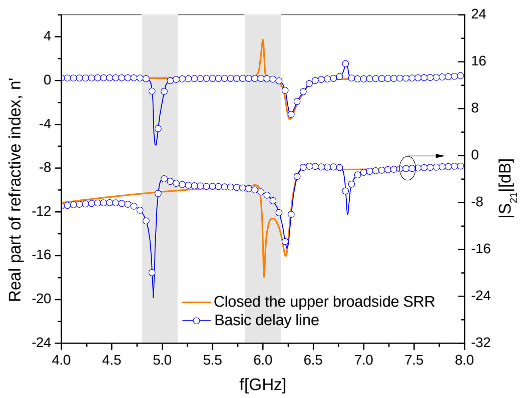


Fig. 10.Real part of index of refraction and S_{21} for the upper broadside SRR closed (Fig. 9b). Rectangular bars denote the changes in responses

Delay line with the single SRR closed (Fig. 9a), exhibits the same response as the single broadside coupled SRRs (Fig. 3. and Fig. 4.). It can be seen that the novel delay line has only two narrow, enhanced peaks in the characteristic of group delay: at 4.9GHz (3.4ns) and 6.75GHz (2ns), instead of three peaks: at 4.96GHz (2.7ns), 6.34GHz (1.1ns) and 6.8GHz (1.5ns).

Delay line with the upper broadside coupled SRR closed (Fig. 9b.), exhibits considerably changed characteristics in respect to the basic delay line, as can be seen in Figs. 10 and 11. The first resonance is moved at the higher frequency from 4.96GHz to 5.98GHz, since there is no the broadside coupled SRRs. Instead of two LH bands, there is only upper left-handed band at the same frequency, while the RH band is shifted down below the LH band (Fig. 10).

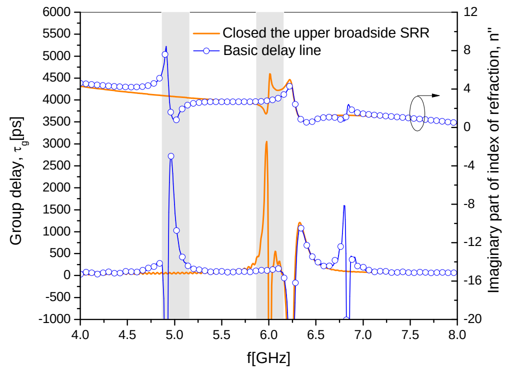
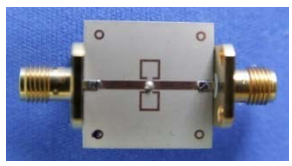


Fig. 11.Group delay and imaginary part of index of refraction (losses) for the upper broadside SRR closed (Fig. 9b). Rectangular bars denote the changes in responses

V. Experimental Results

In order to verify our simulations, the delay line which consists of threeSRRs coupled to microstrip line (Fig. 1.), is fabricated and measured using Agilent PNA E8364A Network Analyzer. Network Analyzer is calibrated with custom designed TRL set shown in Fig. 12a, which provides the measurements of *S*-parameters at certain reference planes and also eliminates the influence of SMA connectors.

(a)



(b)

Fig. 12. Measurement set-up: (a) TRL calibration set, (b) Delay line with SRRs (see Fig. 3. for the details)

Measured *S*-parameters are used as an input data for the retrieval procedure based on Nicolson-Ross-Weir [4] approach.

Simulated and measured S_{21}-parameter and extracted effective index of refraction are shown in Fig. 13. Rectangular bars denote two clearly separated frequency bands with negative refractive index, which is the difference in respect to delay line consisting of two broad-side coupled SRRs which hasthe negative refractive index only in the first band.The first two peaks in the diagram of group delay (Fig. 14) correspond to left-handed bands while the third one is due to right-handed band. Since the first peak is consequence of the single broad-side coupled SRR it is somewhat narrower than in the case of two broad-side coupled SRRs [3].

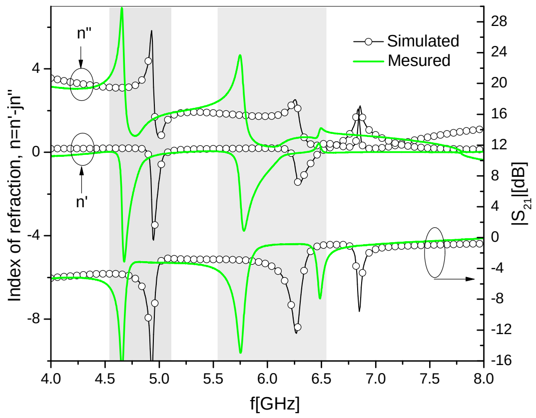


Fig. 13. Simulated and measured $S_{21}$and extracted real (*n'*) and imaginary part (*n''*) of the effective index of refraction

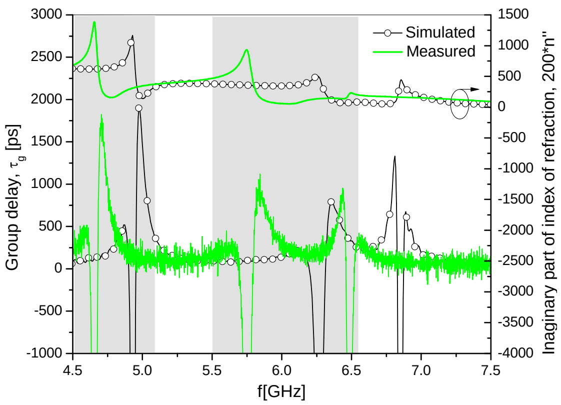


Fig. 14. Simulated and measured group delay,τ_g and imaginary part (*n''*) of the effective index of refraction

Measured results show very good agreement with simulations concerning the shape and the amplitude of the curves, but are shifted for about 6% in respect to simulations due to glue added between two substrates during fabrication that is not taken into account in simulations.

Maximum group delay is measured at the first band at 4.7GHz and is about 1.7ns, while next two peaks are at 5.83GHz and 6.43GHz with delay of 0.94ns and 0.9ns respectively. Those peaks correspond exactly to minimum in the imaginary part of refractive index, n''.

In order to increase group delay, our simulation (Fig. 15.) shows that diameter of via should be increased from 0.2mm, that was used in the experiment, to 0.5mm. In that way maximum group delay in the first band would be 2.7ns at 4.96GHz while at the other bands at 6.33GHz and 6.8GHz delays are 1.1ns and 1.6ns respectively.

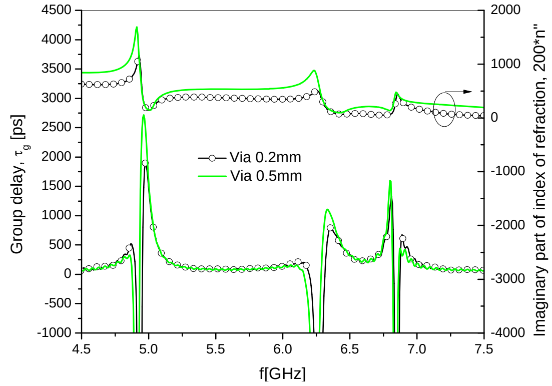


Fig. 15. Simulated group delay,τ_g and imaginary part (*n''*) of the effective index of refraction for two different diameter of via

VI. Conclusion

We present a novel multiband delay line based on two different types of SRRs: broadside coupled SRRs twisted by 90 degrees and single SRR. Novel delay line has two left-handed bands that can be independently tuned by twisting the position of slit in a single SRR or by changing its length. It was shown that single delay line can change the phase for 70 degrees by changing frequency for 100MHz.

Characteristics of proposed delay line can be tuned electronically by PIN diodes, which would open or close certain gaps. This approach would permit creation of electronically reconfigurable delay lines, which electromagnetic properties could be changed in real-time and adjusted to momentary needs. We presented two simple examples of electronically modified delay line using only one PIN diode switched ON/OFF states and placed either on the single SRR or the upper broadside coupled SRR. It was shown that operating frequency of the delay line can be tuned for about 1GHz by switching ON/OFF the diode bias.

Basic delay line is fabricated and measured to verify multiband operation. Very good agreement is observed in all measured and extracted parameters but with frequency shift of about 6% due to glue used in connecting of two-layer substrate that was not taken into account in simulations.

Proposed delay line is suitable for design of multiband feeding networks for frequency scanning antennas.

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