

A Broadband Series Power Divider Using Zero-Degree Metamaterial Phase-Shifting Lines

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Abstract—A metamaterial 1:4 series power divider that provides equal power split to all four output ports over a large bandwidth is presented, which can be extended to an arbitrary number of output ports. The divider comprises four nonradiating metamaterial lines in series, incurring a zero insertion phase over a large bandwidth, while simultaneously maintaining a compact length of $\lambda_0/8$. Compared to a series power divider employing conventional one-wavelength long meandered transmission lines to provide in-phase signals at the output ports, the metamaterial divider provides a 165% increase in the input return-loss bandwidth and a 155% and 154% increase in the through-power bandwidth to ports 3 and 4, respectively. In addition, the metamaterial divider is significantly more compact, occupying only 2.6% of the area that the transmission line divider occupies. The metamaterial and transmission line dividers exhibit comparable insertion losses.

Index Terms—Left-handed (LH), metamaterial, negative refractive index (NRI), power combining, power divider, slow wave.

I. INTRODUCTION

THE electrodynamic behavior of materials possessing simultaneously negative permittivity (ϵ) and permeability (μ) was theoretically investigated by Veselago [1]. These materials exhibit backward-wave propagation characteristics and a negative refractive index (NRI). The first volumetric NRI structure was developed by Shelby *et al.* [2], using an array of split-ring resonators and thin wires. A planar version of the NRI medium was realized by periodically loading a conventional transmission line (TL) with lumped-element series capacitors and shunt inductors in a dual-TL (high-pass) configuration [3], [4]. Various devices that have been developed based on the TL-metamaterial (MM) structure can be found in [5]–[8].

In this letter, a compact, broadband series power divider is presented that is based on the TL-MM structure. By selecting a series rather than a corporate feed topology, the binary-tree corporate-fed networks can be collapsed into a single feed line, reducing significantly the overall area of the structure. Thus, series dividers are more compact and exhibit lower conductor, dielectric, and radiation losses compared to corporate dividers, leading to higher overall efficiencies when used in antenna arrays [9]. However, in conventional TL-based series dividers the ratio of power delivered to each port varies with frequency due to the inherent frequency dependence of the TLs. This work employs

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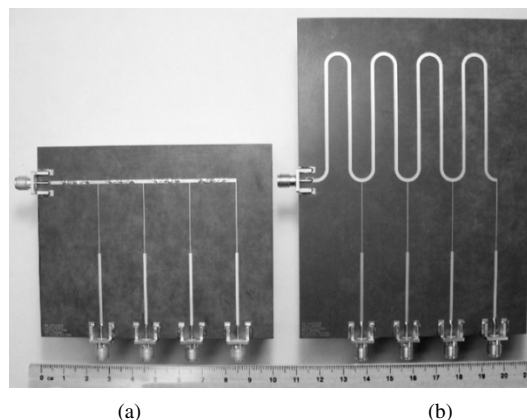


Fig. 1. Photograph of the (a) MM divider and the (b) TL divider.

one-dimensional (1-D) MM phase-shifting lines to develop a broadband 1:4 series power divider that provides equal power split to all four output ports over a significantly larger bandwidth compared to conventional TL series dividers. In addition, the MM divider is very compact, scalable in size, and can be extended to an arbitrary number of ports, therefore it is well suited for various applications including planar antenna feed networks [10] and power-combining amplifiers.

II. DESIGN

Applications that require equal, in-phase power division to a series of loads that are spaced less than a wavelength apart have traditionally used a one guided-wavelength (λ_g) meandered line to feed each of the loads, as shown in Fig. 1(b). However, the resulting power divider structure is large, narrowband, and prone to parasitic radiation caused by scattering from the bends in the meandered lines.

The proposed 1:4 series power divider, shown in Fig. 1(a) and schematically in Fig. 2, employs MM phase-shifting lines to mitigate some of the problems encountered with conventional TL series dividers. The structure consists of four series-connected nonradiating 0° MM lines that feed four 200- Ω loads, spaced $\lambda_0/8$ apart. Thus, at the design frequency, f_0 , the four loads appear in parallel, and the circuit is matched to 50 Ω .

The design of the MM phase-shifting lines was based on the MM unit cell proposed in [7], which can be used to synthesize phase-shifting lines that can incur an arbitrary insertion phase by adjusting the values of the loading elements C_o and L_o . Thus, for a given section of host TL with intrinsic phase shift $\beta_{TL,H} = \omega\sqrt{LC}$ and characteristic impedance Z_0 , the

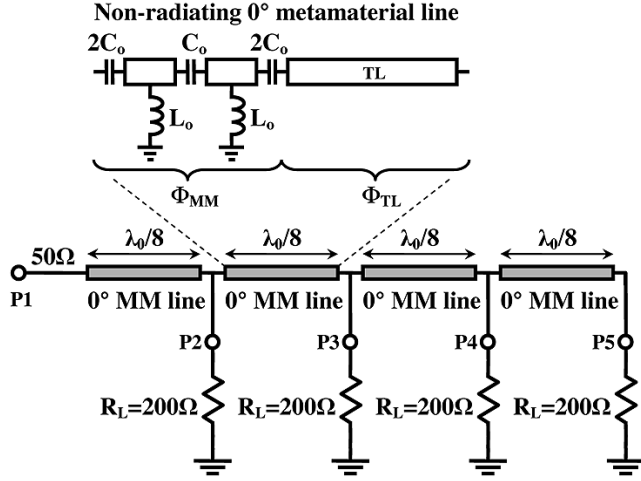


Fig. 2. Schematic diagram of the metamaterial series power divider.

phase shift for an n -stage MM line is given by (1), subject to the impedance matching condition of (2)

$$\Phi_{\text{MM}} = n \left(\omega \sqrt{LC} d_{\text{TL,H}} + \frac{-1}{\omega \sqrt{L_0 C_0}} \right) \quad (1)$$

$$Z_0 = \sqrt{\frac{L_0}{C_0}} = \sqrt{\frac{L}{C}}. \quad (2)$$

Here, it has been assumed that the phase incurred per unit cell and the lengths of the host TLs are small. L and C are the distributed inductance and capacitance of the host TL, $d_{\text{TL,H}}$ is its the length, L_0 and C_0 are the loading-elements, and ω is the frequency of operation.

The nonradiating 0° MM lines shown in Fig. 2 comprise a section of MM line that incurs a positive insertion phase, Φ_{MM} , and a section of TL that incurs a negative insertion phase, $\Phi_{\text{TL}} = -\omega \sqrt{LC} d_{\text{TL}}$. The MM section is designed to operate sufficiently into the backward-wave region outside the radiation cone on the Brillouin diagram, thus ensuring that it does not radiate. The TL section is inherently a slow-wave structure that also does not radiate. Therefore, by cascading these two slow-wave sections, and ensuring that Φ_{MM} and Φ_{TL} are equal but opposite in value, this results in a nonradiating MM line that incurs a zero insertion phase

$$\Phi_0 = \Phi_{\text{MM}} + \Phi_{\text{TL}} = 0. \quad (3)$$

Thus, (1)–(3) can be used to determine the loading values and TL parameters required to design nonradiating 0° MM phase-shifting lines.

III. SIMULATION AND EXPERIMENTAL RESULTS

The TL and MM dividers were implemented in microstrip technology on a Rogers RT5880 substrate with $\epsilon_r = 2.2$ and height $h = 0.787$ mm at a design frequency at the centre of the PCS1900 band of $f_0 = 1.92$ GHz. The design and simulations were carried out in the Agilent-ADS microwave simulator using MuRata S -parameter models of the chip lumped-elements and nonideal microstrip lines.

The TL series divider employed four meander lines, each with a characteristic impedance of $Z_0 = 70.71 \Omega$, width

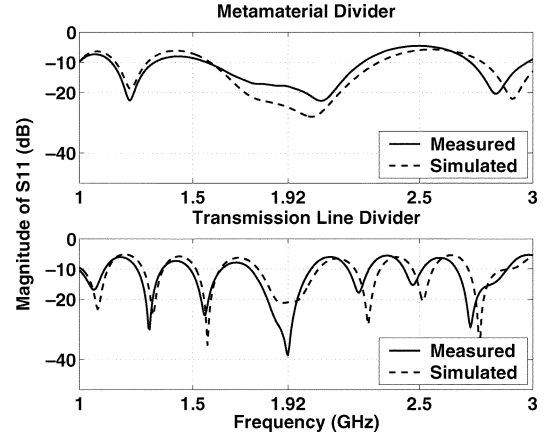


Fig. 3. Measured versus simulated S_{11} magnitude responses for the MM and TL dividers.

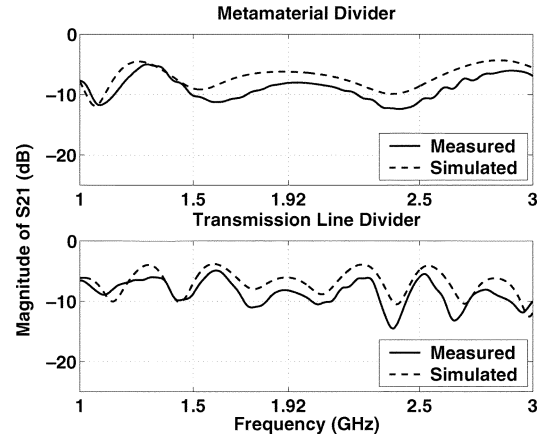


Fig. 4. Measured versus simulated S_{21} magnitude responses for the MM and TL dividers.

$W_{\text{TL},\lambda} = 1.39$ mm and length $\lambda_g = 116.06$ mm. The MM series divider was implemented using four nonradiating 0° MM phase-shifting lines, each consisting of two MM unit cells and a section of TL as shown in Fig. 2. The MM unit cells were implemented using host TLs with $Z_0 = 70.71 \Omega$, width $W_{\text{TL,H}} = 1.39$ mm and length $d_{\text{TL,H}} = 4.48$ mm, and loading element values of $C_0 = 2.2$ pF (Self-Resonant Frequency- SRF = 5 GHz), $2C_0 = 3.3$ pF (SRF = 4 GHz) and $L_0 = 11$ nH (SRF = 5.5 GHz), incurring a total phase-shift of $\Phi_{\text{MM}} = +30.41^\circ$. The section of TL was implemented with $Z_0 = 70.71 \Omega$, $W_{\text{TL}} = 1.39$ mm and $d_{\text{TL}} = 9.77$ mm, incurring a total phase-shift of $\Phi_{\text{TL}} = -30.41^\circ$.

At each of the output ports of the dividers, two quarter-wave-length transformers were added to provide a broadband impedance transformation from the required load impedance of 200Ω to the $50\text{-}\Omega$ test equipment impedance (see Fig. 1). The pertinent values for the two transformers were: $Z_{01} = 79.06 \Omega$, $W_{\text{TL1}} = 0.21$ mm, $d_{\text{TL1}} = 29.92$ mm and $Z_{02} = 158.11 \Omega$, $W_{\text{TL2}} = 1.16$ mm, $d_{\text{TL1}} = 29.07$ mm.

Fig. 3 shows the simulated and measured return loss of the TL and the MM series dividers. The TL divider exhibits a measured -10 dB return loss bandwidth, $\text{BW}_{S_{11}}$, of 0.26 GHz from 1.76 – 2.02 GHz, centred at $f_0 = 1.92$ GHz, while the MM divider has a $\text{BW}_{S_{11}}$ of 0.69 GHz from 1.56 – 2.25 GHz, which corresponds to a 165% increase in bandwidth.

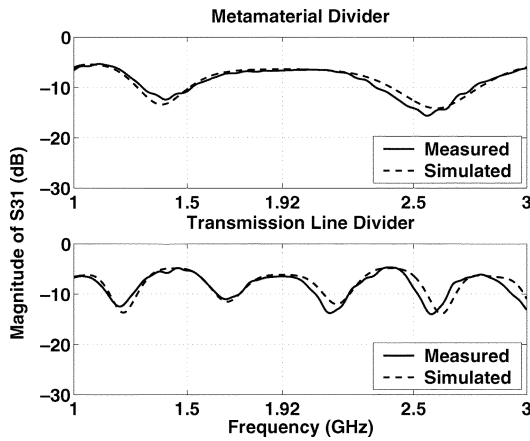


Fig. 5. Measured versus simulated S_{31} magnitude responses for the MM and TL dividers.

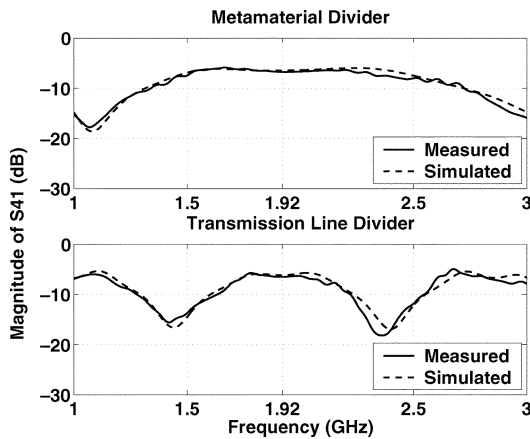


Fig. 6. Measured versus simulated S_{41} magnitude responses for the MM and TL dividers.

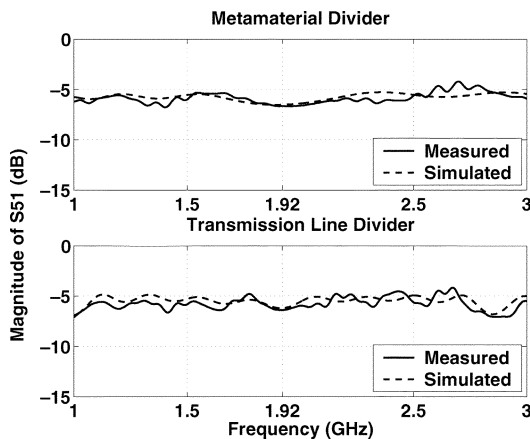


Fig. 7. Measured versus simulated S_{51} magnitude responses for the MM and TL dividers.

Figs. 4–7 show that there is approximately equal power split to all four ports of both the TL and MM dividers at $f_o = 1.92$ GHz. The total measured losses in each path from port 1 to ports 2–5 of the TL divider are 2.21, 0.47, 0.49, and 0.38 dB, respectively, while for the MM divider they are 2.08, 0.62, 0.7, and 0.63 dB, respectively. The total losses for the two dividers are comparable, and include both the material and the reflection losses. The average measured material loss per port is 0.82 dB for the TL divider and 0.88 dB for the MM divider. Since the

losses are expected to increase from port 2 to port 5, the results indicate that there is some power redistributed from port 2 to the other three ports. This can be attributed to imperfections in manufacturing, leading to small deviations from the ideal 0° phase incurred by each of the TL or MM lines, which in turn have a cumulative effect on reducing the amount of power delivered to port 2.

It can be observed that the power delivered to each of the four ports remains constant over a larger bandwidth for the MM divider compared to the TL divider. The TL divider exhibits a -3 dB through bandwidth to port 3, $BW_{S_{31}}$, of 0.31 GHz and a $BW_{S_{41}}$ of 0.54 GHz, compared to a $BW_{S_{31}}$ of 0.79 GHz and a $BW_{S_{41}}$ of 1.37 GHz for the MM divider, corresponding to a 155% and a 154% increase in bandwidth respectively. Moreover, the MM divider occupies an area of 108 mm^2 , which corresponds to a mere 2.6% of the 4098 mm^2 area that the TL divider occupies. Within the frequency range of 1 to 3 GHz, the signal delivered to ports 2 and 5 does not fluctuate beyond $|3 \text{ dB}|$ from the value at $f_o = 1.92$ GHz, therefore a -3 dB bandwidth is not applicable.

IV. CONCLUSION

A new metamaterial 1:4 series power divider has been presented that offers broadband in-phase power division to all output ports, while maintaining a small form factor compared to a conventional transmission line series power divider. The divider is fully planar and offers the flexibility of spacing the output ports arbitrarily apart. Moreover, it can be scaled to an arbitrary number of ports. It is therefore suitable for use in planar antenna feed networks, power combining amplifiers, and synchronized distribution of clock signals in digital circuits.

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