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MICROWAVE DEVICES WITH ENHANCED PHASE-COMPENSATION PRINCIPLE

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ABSTRACT

We report an advanced phase compensation principle, which employs combined backward-forward transmission lines having similar frequency dispersion. Various applications of this principle to the design of microwave devices allow for an exceptionally low dispersion in a wide frequency range while keeping the structure very compact and simple compared to conventional solutions.

To illustrate the idea, we present the performance of (i) phase shifters, (ii) power dividers and (iii) baluns (complete antenna feeders) built on the reported principle.

We support the theoretical estimates by microwave circuit simulations and direct measurements, showing that the novel devices can be easily implemented with simple electronic components.

1. INTRODUCTION

Growing interest to metamaterials and their unusual properties in the course of last several years stimulated invention and design of numerous microwave devices, based on transmission-line representation of metamaterials [1, 2]. In particular, compact phase shifters [3] and tunable shifters [5] employing a single backward line in place of a conventional forward one, were suggested. Recently, more broadband tunable phase shifters, based on combined backward-forward lines [4, 6], were reported. Within the wide variety of other microwave devices, power dividers [7] and antenna baluns [8] were presented.

With most of the reported applications, the design allows for a relatively moderate miniaturization as compared with conventional solutions (provided that the performance is aimed to be comparable or even better). Moreover, with tunable devices still more complicated circuitry is required to retain matching conditions upon tuning to different shifts, and the use of variable capacitors imposes limitations on the power handling capability.

2. ENHANCED DIFFERENTIAL PHASE COMPENSATION

For further improvement of such electronic devices, we suggest to exploit a differential phase compensation scheme, that employs two combined forward-backward lines with similar frequency dispersion (Fig. 1). As a result of appropriate parameters adjustment, differential phase shift ψ remains very stable in frequency, despite remarkable variations of the shifts in each branch, ϕ_1 and ϕ_2.

An illustration of this principle is presented in Fig. 2, where the differential phase shift between the two highly dispersive lines is shown. The two lines have slightly different parameters, providing certain phase difference between them, yet keeping this difference almost invariant in a certain frequency range.

Operation of the proposed scheme can be analytically studied using the transmission matrices of the subcomponents. In contrary to the approximate description followed, e.g., in [3], this approach is not limited to small phase shifts per unit cell, enabling to model reliably arbitrary values.

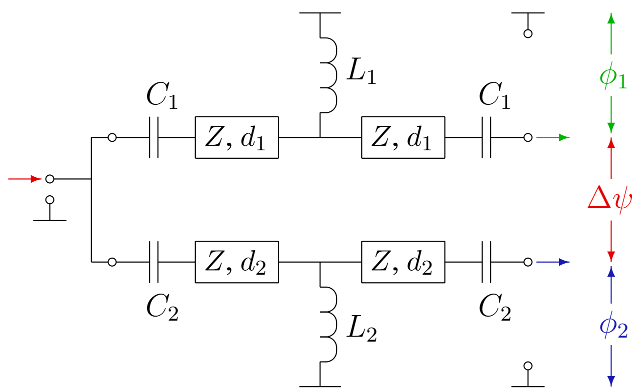

Figure 1. One stage of the phase compensating line.

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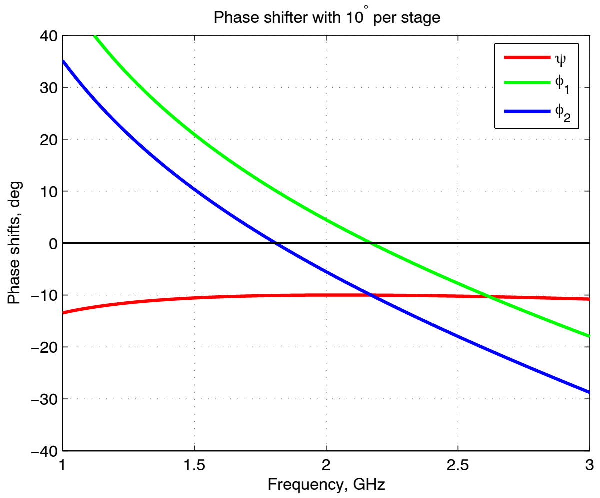

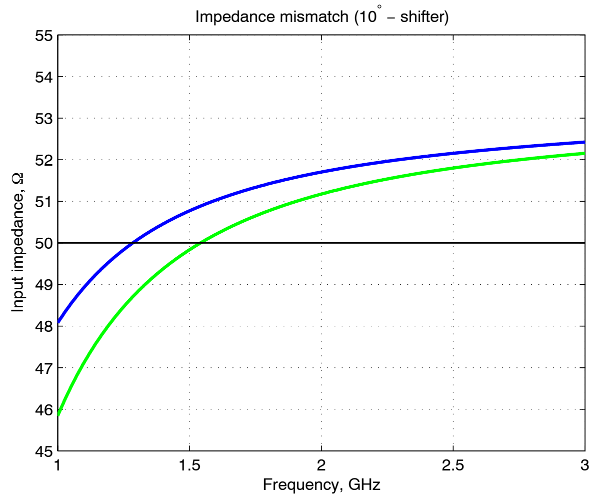

Figure 2. Differential phase compensation (one stage). Top: frequency dependence of the phase shifts in the two lines, ϕ_1, ϕ_2 (blue and green curves), and their difference ψ (red flat curve). Bottom: input impedances of the two lines.

Total transmission matrix for one stage of a combined backward-forward line is

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} = A_{\mathrm{C}} \cdot (A_{\mathrm{TL}} \cdot (A_{\mathrm{L}} \cdot (A_{\mathrm{TL}} \cdot A_{\mathrm{C}}))) \,, \tag{1}$$

where the standard transmission matrices for inductance and capacitances, arranged in a way shown in Fig. 1, are, respectively,

$$A_{\mathrm{L}} = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{j\omega L} & 1 \end{pmatrix} \quad \text{and} \quad A_{\mathrm{C}} = \begin{pmatrix} 1 & \dfrac{1}{j\omega C} \\ 0 & 1 \end{pmatrix} \tag{2}$$

and for a normal transmission line segment

$$A_{\mathrm{TL}} = \begin{pmatrix} \cos(\beta d) & jZ\sin(\beta d) \\ \dfrac{j\sin(\beta d)}{Z} & \cos(\beta d) \end{pmatrix} \tag{3}$$

(β is the propagation constant and Z is the wave impedance of the TL segment).

Then the input impedance Z_{in} can be then calculated from A elements, and the output amplitude and phase shift along one line can be found from the complex transmission coefficient $H = T \exp j\phi$:

$$H = \frac{1}{a_{11} + \dfrac{a_{12}}{Z_{\mathrm{in}}}} \tag{4}$$

For ideal matching, it is required that the impedance Z of the forward TL segments must be equal to the impedance of the backward $L-C$ arrangement:

$$Z = \sqrt{\frac{L}{C}} \tag{5}$$

Under this condition, backward and forward bands merge at the matching frequency ω_m, so that no additional band gap appears [3]:

$$\omega_m^2 \approx \frac{1}{2} \frac{1}{\sqrt{LC}} \frac{v_{\mathrm{ph}}}{d} \tag{6}$$

where v_{ph} is the phase velocity in the TL segments ($\beta = \omega / v_{\mathrm{ph}}$). Accordingly, the combined line operates in a forward regime above ω_m, and in a backward one — below ω_m.

An advantageous aspect is, that the operational frequency (around ω_m) and the impedance Z_{in}, both determined by L, C and d, allow for independent adjustment (obviously, one can tune L/C ratio keeping $L \cdot C$ constant, and vice versa). This means that design can be optimized for a desirable frequency range and at the same time for any required input impedance.

Several stages (unit cells) of Fig. 1 can be connected in series, providing corresponding multiplication of the shift value without any remarkable degradation of performance.

3. PHASE SHIFTER

The advantages of the differential scheme described above can be clearly demonstrated when applied to the design of phase shifters [9].

If the components of the two parallel lines have proportional (with a coefficient ξ) values, so that $C_2 = \xi C_1$, $L_2 = \xi L_1$ and $d_2 = \xi d_1$ (see Fig. 1), than there is a certain phase difference per stage between the two lines. To give an example, Fig. 2 shows phase shifts, produced by each line, as well as the differential shift between them (upper figure), and input impedances of the two lines (lower figure), for a $10°$ shift ($\xi = 1.2$). It can be clearly seen that while the phase course within each line undergoes considerable variation with frequency, the difference is nearly fixed in a wide range. Adjusting the proportionality factor, components values, and stages number, one can achieve an arbitrary phase shift with a few stages of Fig. 1.

Clearly, the smaller is the proportionality factor ξ, the more similar are the dispersion curves of the two lines. This leads to a higher frequency stability, but also to a smaller phase shift per stage. Generally,

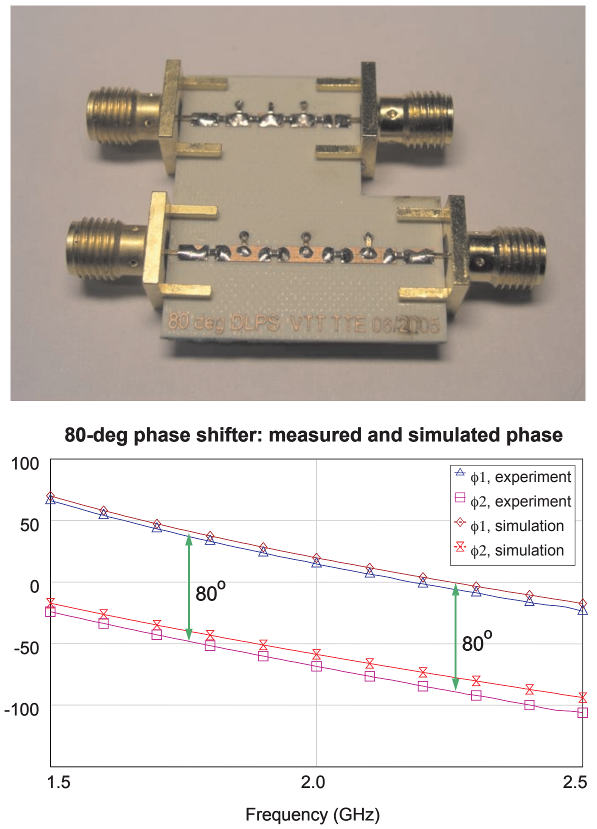

Figure 3. 3-stage phase shifter, designed for $80°$ shift (power divider for feeding the two lines is not implemented). Frequency dependence of the phase shifts along the two lines of the prototype (experimental data compared with simulations). Differential phase shift is indicated by vertical arrows.

with ξ being around 2, it is possible to achieve an arbitrary phase shift value up to $180°$ with 5 stages or less.

When the two lines have proportional parameters, it follows from relation (5) that $\omega_1 \approx \xi^2 \omega_2$. The best performance is then observed around the optimal frequency $\omega_{\rm op} \approx \sqrt{\omega_1 \cdot \omega_2}$.

For any practical implementation, however, the operational range should not include the matching frequencies (6) for the first and second lines, ω_1 and ω_2, because in reality perfect matching condition (5) cannot be reliably realized, and small bandgaps will appear around these frequencies, drastically affecting the performance. Accordingly, the closer the operational range is to the matching frequencies, the more strict requirements are imposed on the impedance matching. On the other hand, for a range lying well within $\omega_2 < \omega < \omega_1$, a slight mismatch in Z can be acceptable.

The stronger is mismatch, however, the stronger impedance varies with frequency, leading to subdued performance. Accordingly, the phase shift per unit cell should not be too small, to ensure that the bandgaps do not fall into the operation range (the two curves in Fig. 2 (top) are well apart).

A sample of the phase shifter, providing $80°$ phase shift in three stages, was implemented using microstrip technology (Fig. 3, top). The performance of this device was evaluated experimentally, and experimental results show excellent agreement with simulations (Fig. 3, bottom), demonstrating that the differential phase shift retains its value in a broad frequency range.

4. POWER DIVIDER

The same principle can be exploited for miniaturization of power dividers. This implies a particular case when the two lines of Fig. 1 are equivalent and provide a $90°$ ($-90°$) shift each. In this way, one can substitute a conventional Wilkinson divider, which exploits two forward TL arches, occupying much larger space.

For an illustration, we present the simulation data for a divider comprising two stages of a combined backward-forward line with $C = 1.16$ pF, $L = 5.4$ nH, $d = 3.1$ mm in place of a simple forward TL arch as in a standard Wilkinson design. Such a line provides $-45°$ phase shift per stage while the impedance is adjusted so that all the ports are matched to 50 Ω.

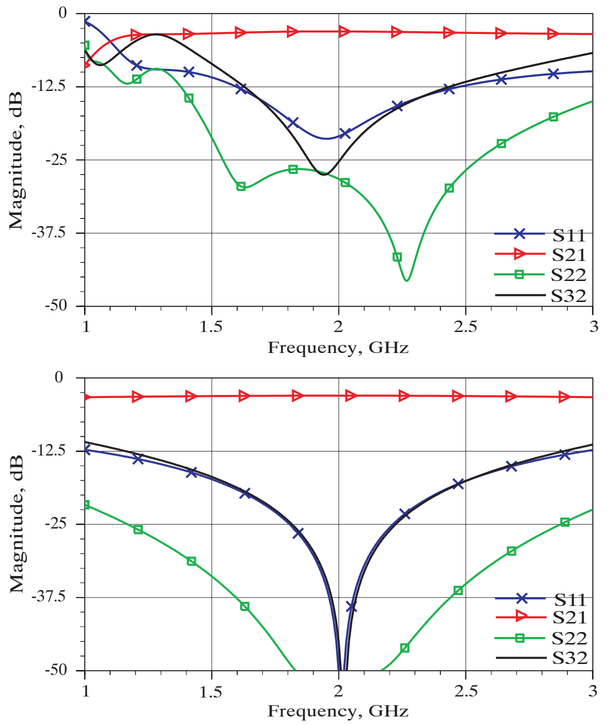

Figure 4. Compact power divider comprising two combined backward-forward lines with two stages each. Frequency dependence of the S-parameters. For comparison, the characteristics of a conventional Wilkinson divider are shown (lower figure).

Fig. 4 shows that the performance of this device is comparable with that of a conventional design. At the same time, the area required for the backward-forward line divider (here, less than 1.5 cm^2), is two times smaller than for the corresponding standard one.

Clearly, further optimization with regards to particular needs would offer still more advantageous solutions.

5. ANTENNA FEEDER (BALUN)

Application of the described compact phase compensation to antenna feeds would allow for a conceptual miniaturization. It is known that the use of combined backward-forward lines can reduce the dimensions of a Wilkinson balun [8]. We suggest a further miniaturization by merging the power divider and balun itself into one structure, comprising a few stages of backward-forward lines in a differential arrangement, providing 180° phase difference at the output while being matched to the input and to the antenna (the layout is the same as in Fig. 1).

In the example used here, a 4-stage differential arrangement was tested, with one line employing $C = 4$ pF, $L = 7$ nH, $d = 3$ mm and the other $C = 10$ pF, $L = 17.5$ nH, $d = 7.5$ mm. These four stages comprise the whole feed structure from the input to the antenna and thus offer significant reduction in size (more than two times, to our estimates).

The simulated performance of this device is shown in Fig. 5 (for simplicity, antenna was modelled by a loading resistor). The data show that the required phase difference in perfectly maintained in a broad frequency range, while the matching is sufficient for a reasonable bandwidth.

We believe that this design can be adopted for a required performance and that even more efficient miniaturization is possible.

6. CONCLUSIONS

The reported phase compensation principle is shown to offer fruitful opportunities for the design of various microwave devices.

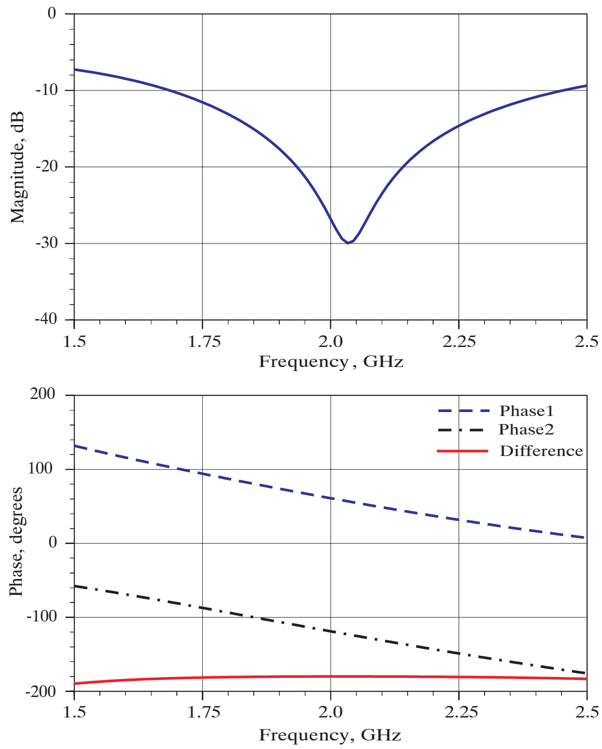

Figure 5. Compact antenna balun comprising two combined backward-forward lines. Frequency dependence of the input reflection and of the phase difference at the output is shown.

Corresponding phase shifters are characterized with negligible frequency dependence in a wide frequency range. We show that phase deviation can be less than 1° within a 20% bandwidth while excellent impedance matching is retained.

The power dividers offer performance, comparable with conventional Wilkinson dividers, occupying, however, two times smaller area or even less.

For antenna feeders, the reported principle opens an excellent opportunity to combine a power divider and an adjacent balun into one simple structure, also leading to essential size reduction while keeping characteristics, comparable with conventional assemblies.

It is important to note that depending on the practical needs, TL segments can be substituted with lumped components (in a low-pass arrangement).

We conclude that the proposed scheme offers exceptionally advantageous characteristics being, at the same time, easily realizable with simple electronic components. It is, therefore, suitable for relatively high power while being devoid of nonlinear effects.

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