A New Circuit Topology for Continuous Group Delay Synthesis

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***Abstract*—A new circuit topology is realized in order to synthesize group delay continously. The circuit is based upon a new variable coupling coefficient coupled line section and a microstrip feedback loop. The new variable coupler is designed by periodically loading an edge coupled microstrip coupler. With this new design, coupling variation of more than 10 dB may be achieved. To the best of the authors knowledge, this is the first report of this type of microstrip coupler. The complete circuit consumes no dc power and exhibits more than 500 ps of continuous variable true time delay. Insertion loss is better than 3 dB and return loss is better than 15 dB.**

***Index Terms*—Group delay, periodic loading, phase shifter, true time delay, variable microstrip coupler.**

I. Introduction

TRUE time delay (TTD) lines have many applications in modern microwave systems. They enable rapid and accurate tuning of system delay with a DSP in applications such as adaptive error cancelation in high power amplifiers. True time delay lines have been implemented in numerous ways. The simplest method for achieving true time delay is with a fixed coaxial delay line. The nonlinear delay line (NDL) has been demonstrated for applications in phased array antenna systems [1], [2]. A variable optical directional coupler was utilized with a long fiber delay line to achieve continuous beam steering in the sub 1200 MHz band [3].

In this work, a new variable microstrip coupler is presented as the operating core of a TTD line. The variable coupling coefficient provides the mechanism to change group delay.

II. Variable Microstrip Coupler

The new variable microstrip coupler is derived from a standard edge coupled impedance type coupler. In this new case, the mechanism varying the coupling coefficient is that of the electrical length of the coupled microstrip section. By varying the electrical length of the coupled section from 90° to 180° the coupling coefficient is varied from maximum to minimum. This coupling response is periodic in electrical length with a 180 degree periodicity. The change in electrical length is achieved with variable loading of the coupled line sections with a periodic structure.

A schematic of the variable coupler section is shown in Fig. 1. In the design, eight periods are utilized with a periodicity of approximately 11°. Alpha Industries Flip-Chip varactor diodes are used. The two coupled microstrip lines are each loaded on the noncoupling edges with the diodes. The capacitive loading causes a slow wave effect, thereby lengthening the line electrically. Since the varactors are reversed biased, the coupler consumes no dc power.

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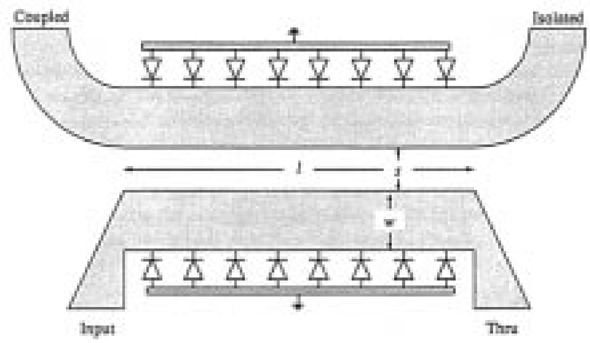

Fig. 1. Variable microstrip coupled line section.

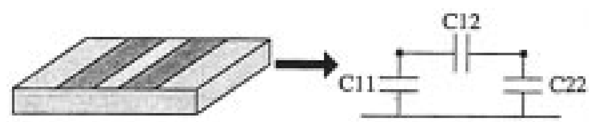

Fig. 2. Equivalent capacitances for microstrip coupled lines.

A. Even–Odd Mode Impedances and Coupler Bandwidth

Analysis of the variable coupler may be performed by modifying the simple even–odd type analysis usually used for couplers [4]. Fig. 2 illustrates the equivalent capacitances of the circuit. The even and odd mode impedances are given by

$$
\begin{aligned}
Z_{0e} &= \frac{1}{v(C_{11} + C_{\mathrm{var}})} \\
Z_{0o} &= \frac{1}{v(C_{11} + 2C_{21} + C_{\mathrm{var}})}
\end{aligned} \tag{1}
$$

where C_{var} is the variable capacitance of the varactor diode and v is the phase velocity of the mode. Since the characteristic impedance of the coupler is given by $Z_0 = \sqrt{Z_{0e} Z_{0o}}$, the coupler's return loss performance is interrelated with the coupling coefficient. This phenomena poses a limitation on the circuits bandwidth and the range of coupling coefficient variation. In order to maximize the usable range of the variable coupler, the unloaded characteristic impedance of the coupler is chosen to be higher than 50 Ω. Thus, when loading occurs the input VSWR remains below 2:1.

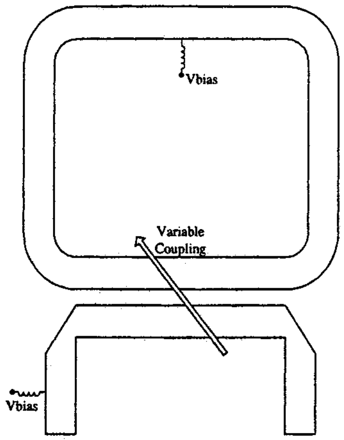

Fig. 3. Schematic of the new group delay synthesizer circuit.

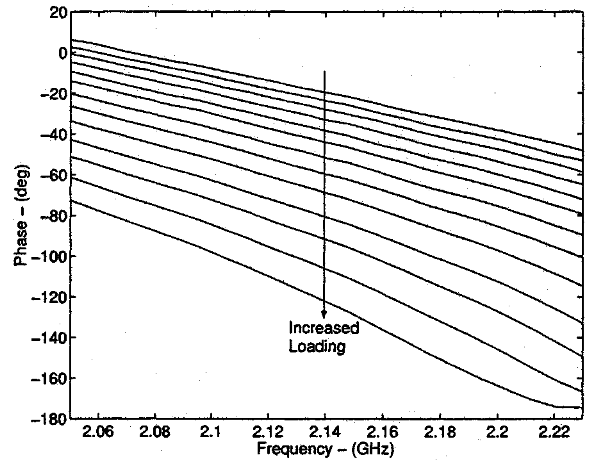

Fig. 4. Insertion phase of the group delay synthesizer.

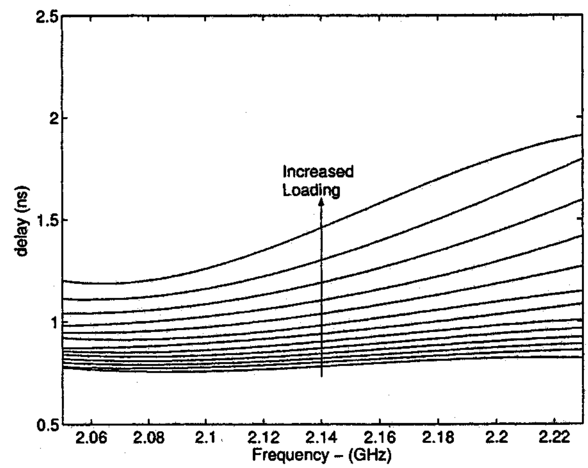

Fig. 5. Group delay $(-\partial\phi/\partial\omega)$.

B. Coupling and Insertion Phase

The variable microstrip coupler is implemented on RT/Duroid 6010 substrate thickness 50 mil. The characteristic impedance of the unloaded coupler is chosen as 75 Ω, the electrical length of the unloaded coupler is 90°. The unloaded coupling coefficient is 4 dB. Simulations of the coupler section show a 10 dB variation of coupling coefficient and the insertion phase of the coupler increases by approximately 90°. Thus, as the coupler's electrical length increases from 90° to 180°, the coupling between lines decreases as expected.

III. Group Delay Synthesizer

Phase shifting circuits based upon variable couplers have been proposed in the optical domain [5], however, these circuits have been demonstrated at relatively low radio frequencies and require a complex process to fabricate the coupler. In this work, the variable microstrip coupler discussed in Section II is combined with a 360° feedback loop to create a new group delay synthesizer circuit. The circuit may be consider a phase slope shifter, as well. The new group delay synthesizer circuit is illustrated schematically in Fig. 3. The frequency dependence of the feedback loop presents a bandwidth limiting parameter as the electrical length of the loop varies. The useful delay bandwidth of the synthesizer depends upon group delay flatness requirements and may be limited.

The feedback loop is a one wavelength long microstrip line connecting the coupled and isolated ports of the variable microstrip coupler. The new synthesizer works by passing a fraction of the input signal into the feedback loop via the coupled port. The coupled signal is delayed by the length of the line. It re-enters the coupler through the isolated port, now serving as the input port for the feedback line. This signal is again divided between the coupled port and the through port. The process results in an infinite series of delayed signals which sum at the output port with a delay. The delay process is described by

$$E_{\rm out} = E_{\rm in}\left[(1-x)e^{j\theta_1} + \frac{x^2 e^{j\theta_2}}{1-(1-x)e^{j(\theta_1+\theta_2)}}\right] \qquad (2)$$

where θ_1 is the variable electrical length of the coupler (due to the variable slow wave effect) and θ_2 is the length of the feedback line, $x/(1-x)$ is the ratio of coupled to through voltages. For the case when $x=0$ (no coupling) $E_{\rm out} = E_{\rm in}e^{j\theta_1}$, which is just the phase shift through the coupler. When x is not zero, the signal passes around the feedback line repeatedly, which increases the signal group delay. The feedback line can also be considered as a coupled inductor.

IV. Measured Results

The new variable group delay synthesizer was fabricated on 50 mil thick RT/Duroid 6010, dielectric constant $\epsilon_r = 10.2$. Sixteen varactor diodes were used in two sets to vary the coupling coefficient of the coupler. The circuit required reverse dc bias from 1.2 Vdc to 2.3 Vdc in order to achieve its full operating range. Both bias signals shown in Fig. 3 are tied together. The small tuning voltage range and lack of dc current requirements ideally suits the circuit to applications where the driver is a DSP, such as in adaptive feed forward power amplifiers. All measurements were made on an Agilent 8510C network analyzer.

The measured phase response of the new group delay synthesizer is shown in Fig. 4. The plot shows the phase of S_{21} at various bias voltages. The slope of the phase signal becomes

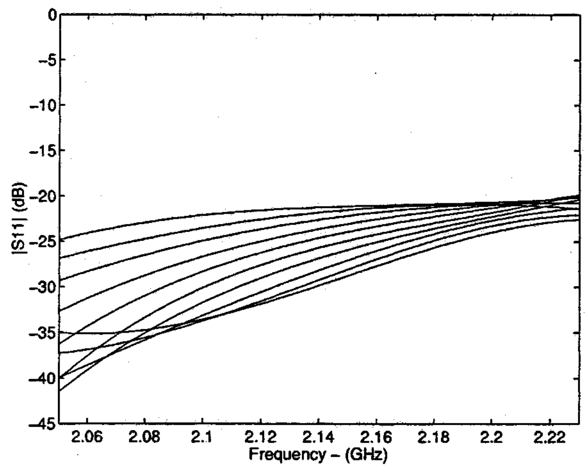

Fig. 6. Measured return loss of group delay synthesizer.

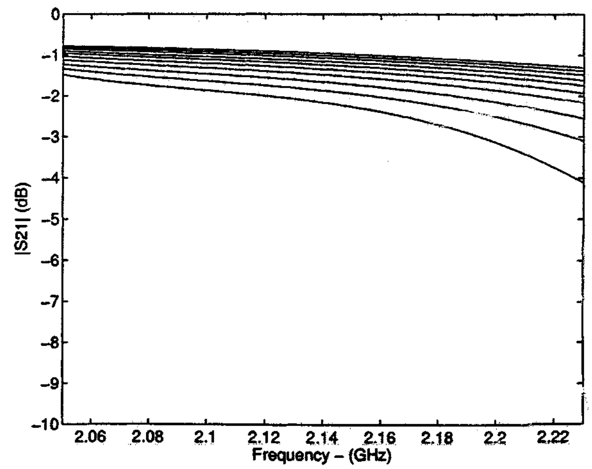

Fig. 7. Measured insertion loss of group delay synthesizer.

steeper with increased capacitance, thereby providing additional delay. The group delay measured by the network analyzer is given in Fig. 5. The network analyzer was set to 5% smoothing for phase and group delay measurements. Minimum group delay variation is approximately 500 ps. Center band group delay variation is approximately 1500 ps. Group delay flatness is affected by the change in electrical length of the feedback loop with frequency. Measured return loss is plotted in Fig. 6, insertion loss in Fig. 7.

V. CONCLUSION

A new group delay synthesizer circuit is presented. The circuit is based upon a variable coupling coefficient microstrip coupler with a one wavelength feedback loop connecting coupled and isolated ports. The new coupler presented is the first to utilize a periodically loaded edge coupled microstrip coupler. The periodic loading varies the coupler's electrical length, thereby varying the coupling coefficient from maximum to minimum. The circuit exhibits a minimum of 500 ps variable group delay, return loss of better than 15 dB and insertion loss of less than 3 dB. The circuit consumes no dc power and is readily controlled by a DSP in applications such as adaptive error cancelation in high power amplifiers.

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