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Tunable C-Section Phaser for Dynamic Analog Signal Processing

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Abstract

This paper proposes a tunable phaser consisting of a conventional C-section incorporating two small-value varactors. Theoretical analysis shows that the varactors add a transmitting pole to the frequency response of the phaser and that this pole addition leads to a wide passband in addition to the group delay tunability provided by the varactors. A proof-of-concept design example is provided. Such a tunable phaser is expected to find wide applications in *dynamic* Real-Time Analog Signal Processing (R-ASP).

1 Introduction

Real-Time Analog Signal Processing (R-ASP) is a potential alternative to dominantly digital radio technology, given its high-speed, low-consumption and frequency-scalability benefits [1–4]. The key component of a R-ASP system is the phaser [1], a component providing specified group delay versus frequency response, which has been widely used in Dispersive Code Multiplexing (DCM) [2], frequency steering arrays [3], Real-Time Fourier Transform (RTFT) [4], etc.

In future applications with dynamic environments, tunable phasers will be needed to process signal that adapt to the changing environment. Such applications include channel equalization in fading wireless environments and crest-factor-reduced power amplifiers in wideband OFDM. Tunable phasers have been reported in several technologies, such as for instance Electromagnetic Bandgap (EBG) structures [5], amplifying feedback loops [6] and loss-gain C-section pairs [7]. This paper presents a wideband tunable C-section phaser, which, compares to the mentioned technologies, exhibits favorable features in terms of flexibility, simplicity and stability, and hence represents a promising phaser technology towards dynamic R-ASP.

2 Structure and Analysis

The proposed tunable phaser is shown in Fig. 1(a). It is composed of a C-section phaser incorporating two varactors, C_1 and C_2. Figures 1(b) and 1(c) show the corresponding equivalent even and odd circuits, respectively, with characteristic impedances Z_e and Z_o, and electrical length θ. All ports impedances are set to 50 Ω. The even and odd mode input impedances of the phaser are

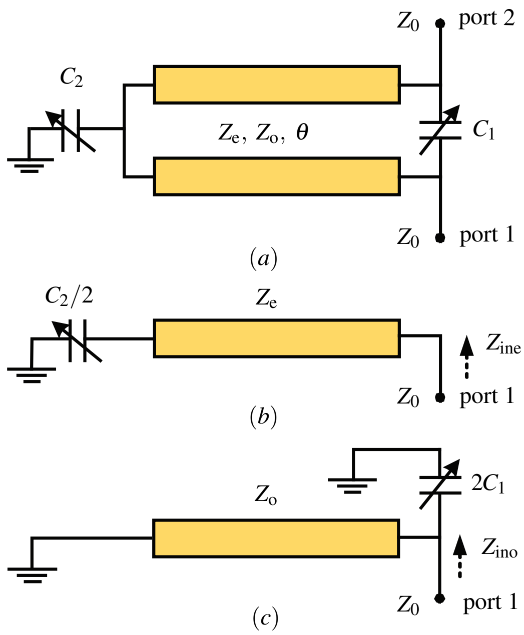

Figure 1. Proposed tunable C-section phaser. (a) Complete structure. (b) Even mode equivalent circuit. (c) Odd mode equivalent circuit.

$$Z_{\text{in,e}} = Z_e \frac{2X_2 + jZ_e \tan\theta}{Z_e + 2jX_2 \tan\theta}, \tag{1}$$

$$Z_{\text{in,o}} = \frac{X_1}{2} \;//\; jZ_o \tan\theta, \tag{2}$$

where X_1 and X_2 are the reactances associated to C_1 and C_2, respectively, i.e. $X_1 = \frac{1}{j\omega C_1}$ and $X_2 = \frac{1}{j\omega C_2}$. The S-parameters of the phaser may then be found by inserting (1) into [8]

$$S_{11} = \frac{Z_{\text{in,e}} Z_{\text{in,o}} - Z_0^2}{(Z_{\text{in,o}} + Z_0)(Z_{\text{in,e}} + Z_0)}, \tag{3}$$

$$S_{21}=\frac{Z_{\text{in,e}}Z_0-Z_{\text{in,o}}Z_0}{(Z_{\text{in,o}}+Z_0)(Z_{\text{in,e}}+Z_0)}. \tag{4}$$

This yields intricate expressions providing little insight into the operation of the device. We shall therefore consider next simplifications corresponding to two different frequency regimes, and for low C_1 and C_2 values as required practically.

Situation I: Relatively Low Frequency
At sufficiently low frequencies, assuming small C_1 and C_2, the admittances $j\omega C_1$ and $j\omega C_2$ are negligible, and the varactors may therefore be ignored. In this case, the device is equivalent to a classical C-Section, with $S_{11}=0$ and $S_{21}=1$, and monotonously increasing group delay versus frequency [9].

Situation II: Frequency ω_0 where $\theta=\theta_0=\pi/2$
When the phaser operates at the frequency ω_0 where $\theta=\theta_0=\pi/2$, Eq. (1) and (2) reduce to

$$Z_{\text{in,e}}=Z_{\text{e}}^2/(2X_2), \tag{5}$$

and

$$Z_{\text{in,o}}=X_1/2. \tag{6}$$

In this case, ensuring matching, i.e. $S_{11}=0$, requires setting $Z_{\text{in,e}}(\theta_0)Z_{\text{in,o}}(\theta_0)=Z_0^2$, according to (3). Using (5) and (6), this condition straightforwardly translates into the relation

$$\frac{C_2}{C_1}=\frac{X_1}{X_2}=4\left(\frac{Z_0}{Z_{\text{e}}}\right)^2 \tag{7}$$

between C_1 and C_2. Since this condition corresponds to a zero of (5) and since the system being assumed lossless, this relation corresponds to a pole in (4), i.e. to a transmission pole in filter language. Equations (5) and (6) with (7) reduce Eq. (4) to

$$S_{21}(\omega_0)=\frac{2Z_0-X_1(\omega_0)}{2Z_0+X_1(\omega_0)}=\frac{2Z_0+j/(\omega_0C_1)}{2Z_0-j/(\omega_0C_1)}, \tag{8}$$

corresponding indeed to $|S_{21}(\omega_0)|=1$. The corresponding phase and group delay of the phaser are found as

$$\varphi_{21}(\omega_0)=-2\text{atan}\left(\frac{\|X_1(\omega_0)\|}{2Z_0}\right)=2\text{acot}(2Z_0\omega_0C_1), \tag{9}$$

and

$$\tau_{21}(\omega_0)=-\frac{d\varphi_{21}}{d\omega}=\frac{4Z_0C_1}{1+(2Z_0\omega_0C_1)^2}, \tag{10}$$

respectively. The latter equation reveals that the group delay monotonously decreases versus frequency and also decreases as C_1 increases at $\omega\approx\omega_0$.

From the above analysis, it appears that the value of the varactor influences the group delay of the conventional C-section. Specifically, the peak of group delay progressively moves towards lower frequency as C_1 and C_2 increase while respecting the condition (7).

3 Simulation Validation

This section simulates the proposed phaser to validate the analysis. We set $Z_{\text{e}}=100\ \Omega$ and $Z_{\text{o}}=25\ \Omega$. The frequency of the pole is $f_0=5$ GHz. The insertion loss (S_{21}) and group delay (τ) are plotted in Fig. 2 and Fig. 3, respectively.

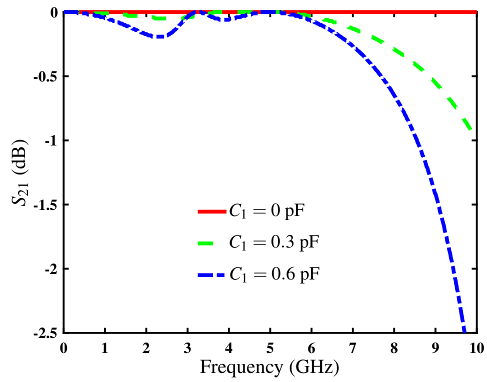

Figure 2. Transmission parameter versus frequency for different values of C_1 and C_2 satisfying (7) (matching condition).

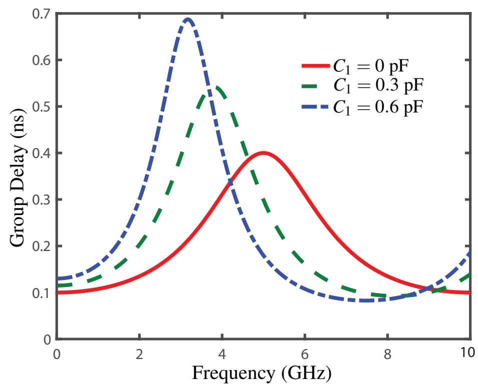

Figure 3. Group delay versus frequency for the same parameters as in Fig. 2.

It may be seen in Fig. 2 that when the value of the capacitances is small, the inserting loss of the phaser below its cutoff frequency region is very low and may be neglected. However, insertion loss increases with increasing C_1. Figure 3 shows that as C_1 varies from 0 pF to 6 pF, the group delay peak value increases from 0.4 ns to 0.69 ns and moves from 5 GHz to 2.6 GHz. So, there is a trade-off between tunability and insertion loss.

4 Conclusion

A novel wideband tunable C-section phaser has been proposed, analyzed and demonstrated. This device may potentially enable novel dynamic R-ASP systems.

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