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A novel real-time Fourier and inverse Fourier transforming system based on non-uniform coupled-line phaser

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ABSTRACT

A novel real-time Fourier and inverse Fourier transforming (RTFaIFT) system realizing both positive and inverse transformations is designed and verified, using non-uniform coupled-line phaser. Two kinds of Fourier transformations are integrated within one system for the first time. This system can map the spectrum of the input signal into a waveform in time domain whose amplitude mimics the spectrum magnitude, owing to the frequency-varying group delay (GD) response of the phaser. Furthermore, the correspondence between the output waveform and the spectrum of the input signal is given for accurate analysis of the spectrum. This configuration possesses the characteristic of compact structure, simple design procedure, and perfect performance, consisting of a mixer, a phaser with linear group delay, a diode, and a LPF. For experimental demonstration, a RTFaIFT system operating at 6 GHz is designed and fabricated, the bandwidth of which is 4 GHz with −0.5 ns/GHz GD slope. Both single- and double-pulse signals have been chosen as the test signals to verify the performance of the RTFaIFT system, respectively. The experimental results agree well with simulation and theoretical results.

1. Introduction

Real-time analog signal processing (R-ASP), inspired by ultrafast optics [1] and CMOS technology [2], provides an effective means to monitor, manipulate, and process radio signals in real time. Compared with traditional digital signal processing (DSP), real-time signal processing operates on the signals instantly in the time domain and has more superior characteristics in the ultra-high frequency (UHF) (300 MHz–3 GHz) especially in Terahertz region, which overcomes the defects of DSP such as low efficiency, high consumption, high cost from A/D and D/A conversion, and so on. R-ASP system has been widely applied to modern communication, such as Fourier transformer for processing the spectrum [3], real-time spectrum sniffer for measuring and analyzing complex non-stationary signal [4], pulse position modem (PPM) for RFID [5], time reversal for temporal and spatial focusing characteristics [6], etc. Among those applications, real-time Fourier transforming system is the most typical ASP system.

Real-time Fourier transforming (RTFT) system maps the magnitude spectrum to a temporal waveform, enabled by dispersive delay structures with linear group delay. In order to realize RTFT system, multiple design methods have been proposed for group-delay engineering of the linear-group-delay phaser. To the author's knowledge, the existing microwave RTFT system was realized by the cascade C-section structure (CCS) [3]. However, without closed-form solution, the approximate algorithms, for instance, the genetic algorithm [7] and the predistortion algorithm with space mapping [8], call for expensive time expenses and complexity. Besides this, the structure in [3] is extremely huge, with two phasers, four mixers, and so on, leaving behind a lot of problems on fabrication and integration. When it comes to real-time inverse Fourier transforming (RTIFT) system [9], the configuration is similar to the one in [3], with the same devices in different connecting order. However, to the author's knowledge, there is no microwave system integrating both two transforms up till now.

In this paper, we introduced a novel configuration of real-time Fourier and inverse Fourier transforming (RTFaIFT), realizing both RTFT and RTIFT functions. The RTFaIFT system is based on non-uniform coupled-line phaser with linear group delay response [10]. This dispersive structure has smoother group delay performance with smaller ripple, and most importantly, it has standard numerical solution. The proposed system has reduced the number of the devices in contract to the existing systems, consisting of one phaser, one diode, one filter, and three mixers, considerably reducing the structural complexity.

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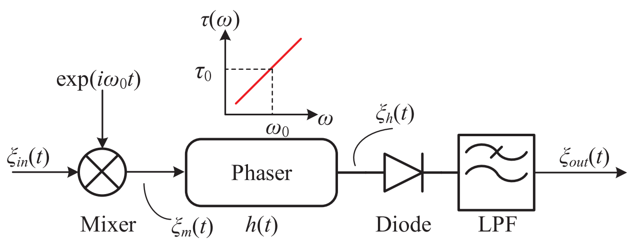

Fig. 1. The construction of the proposed RTFaIFT system.

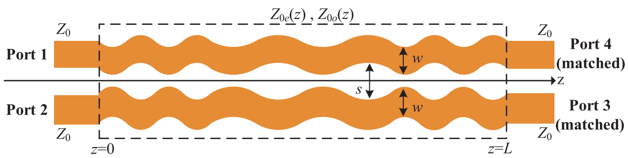

Fig. 2. Non-uniform coupled-line phaser with variable width of the lines w and the space between them s.

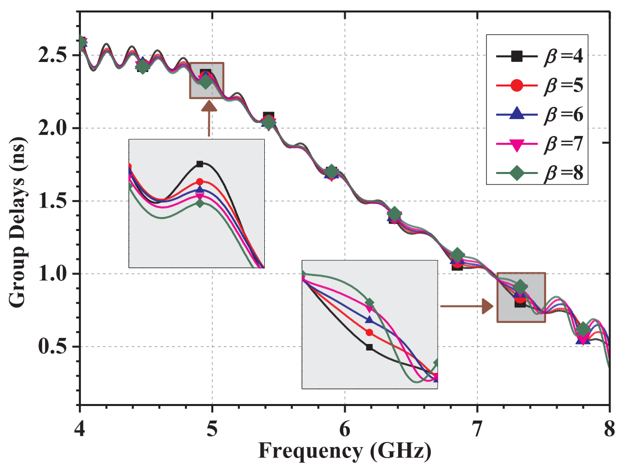

Fig. 3. Group-delay responses of the non-uniform phaser with different β of the Kaiser window function.

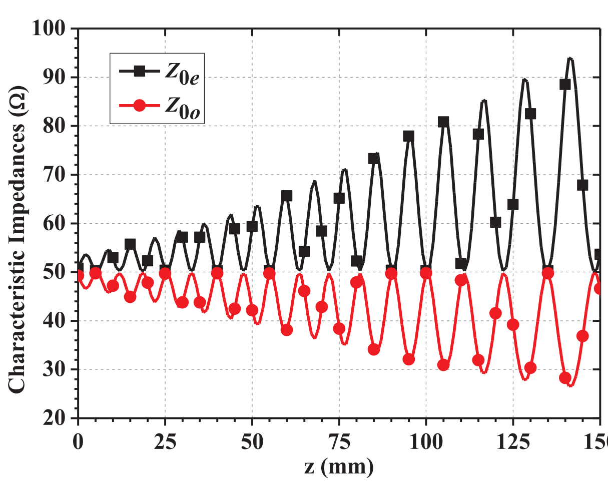

Fig. 4. Calculated even- and odd-mode characteristic impedances, $Z_{0e}(z)$ and $Z_{0o}(z)$, of the non-uniform coupled-line phaser.

2. Theoretical analysis

2.1. Real-time Fourier and inverse Fourier transforming (RTFaIFT) system

The configuration of the novel real-time Fourier and inverse Fourier transforming system is illustrated in Fig. 1. The overall system consists of a modulation unit, a dispersive delay structure made up of the uniform coupled-line phaser with linear group delay, and a signal processing unit. The input signal is modulated with the carrier frequency ω_0 by multiplier. Then the modulated signal propagates through the phaser, among which different spectral components of the modulation signal separate with each other in the light of the mapping laws. Finally, we use rectifier and low-pass filter to extract signal envelope.

Let us consider an input baseband signal $\xi_{in}(t)$, for which spectrum shifting is essential owing to the center frequency ω_0 of the phaser. The modulation signal $\xi_m(t)$ is constituted by a baseband pulse $\xi_{in}(t)$ modulated with carrier frequency ω_0, given as

$$\xi_m(t) = \xi_{in}(t)\cdot e^{i\omega_0 t}. \tag{1}$$

With linear group delay response, the phase response must be a square function of frequency. As a linear system, the phaser has an impulse response as follows [11]

$$h(t) = \int_{-\infty}^{+\infty} e^{i\varphi_0} e^{i\varphi_1(\omega-\omega_0)} e^{i\frac{\varphi_2}{2}(\omega-\omega_0)^2} e^{i\omega t} d\omega, \tag{2}$$

where φ_0, φ_1, and φ_2 are the coefficients of the Fourier series expansion equation.

Then we have the signal $\xi_h(t)$ by transmitting the modulated signal through the phaser, which is described by the convolution of the $\xi_m(t)$ and $h(t)$. The output signal $\xi_{out}(t)$ is obtained by applying the envelope detection to $\xi_h(t)$ [11]

$$\begin{aligned}\zeta_{out}(t) &= |\zeta_h(t)| = |[\zeta_{in}(t)e^{i\omega_0 t}] \otimes h(t)| \\ &= \sqrt{\frac{2\pi}{\varphi_2}} \int_{-\infty}^{+\infty} \zeta_{in}(t) e^{i\tau\frac{(\varphi_1+t)}{\varphi_2}} d\tau\end{aligned} \tag{3}$$

As can be seen from (3), there is some kind of correspondence between the output signal and the Fourier transforming of the input signal. When different mapping laws are defined, the system can realize different transforming, i.e. Fourier transforming and inverse Fourier transforming.

The real-time Fourier transforming can be realized by

$$\begin{aligned}\zeta_{out}[\omega(t)] &= |\zeta_h(t)| = |[\zeta_{in}(t)e^{i\omega_0 t}] \otimes h(t)| \\ &= \sqrt{\frac{2\pi}{\varphi_2}} \int_{-\infty}^{+\infty} \zeta_{in}(t) e^{-i\omega(t)\tau} d\tau\end{aligned}, \tag{4a}$$

$$\omega(t) = -(\varphi_1 + t)/\varphi_2. \tag{4b}$$

While the real-time inverse Fourier transforming can be realized by

$$\begin{aligned}\zeta_{out}[\omega(t)] &= |\zeta_h(t)| = |[\zeta_{in}(t)e^{i\omega_0 t}] \otimes h(t)| \\ &= \sqrt{\frac{2\pi}{\varphi_2}} \int_{-\infty}^{+\infty} \zeta_{in}(t) e^{i\omega(t)\tau} d\tau\end{aligned}, \tag{5a}$$

$$\omega(t) = (\varphi_1 + t)/\varphi_2. \tag{5b}$$

As can be seen from (4a) and (5a), the output signal has identical shape with the envelop of the Fourier transforming spectrum and the inverse Fourier transforming waveform, while the mapping relation between frequency and time is determined by (4b) and (5b), respectively. Compared with the previous configurations of the RTFT system in [3] and inverse RTIFT system in [9], this new structure integrates two transformations into one system, reducing the number of the devices, thus greatly cutting down on the size.

2.2. Group delay engineering for non-uniform coupled-line phaser

The phaser, as the core of R-ASP, brings on time dispersion to the pulse passing through itself by analog with far-field diffraction (i.e. Fraunhofer diffraction). In other words, when a signal propagates through this structure, different spectral components possess different group velocities, thus dispersing with each other on the time domain, while the phaser acts as dispersion medium in this process.