A Novel Frequency Reconfigurable Real-Time RF Edge Detector

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***Abstract*—In this paper, a frequency reconfigurable RF edge detector is presented to sense the edge of signal in its real time. The proposed circuit consists of a tunable 180° hybrid coupler and a tunable delay line, and theory analysis is carried out to find their relation. The delay line connects coupling port and isolation port to achieve a closed loop resonator across all frequency tunning range, which enables edge detection of RF signal in wide frequency range. To prove the design concept, a prototype of tunable microwave edge detector (TED) has been designed, fabricated, and tested, and the measured results match well with simulation and theory. By applying two-channel control voltage, the prototype senses edge of modulated RF pulse signal from 1.9GHz to 2.4GHz in real time.**

***Keywords*— Tunable RF edge detector, reconfigurable microwave circuit, wideband edge detection, real-time RF signal processing.**

I. Introduction

The emerging 5G and NextG technologies enable high data rate and low latency to support multi-user access with extremely wide channel capacity. The offered wide bandwidth in these new technologies require high-end analog-to-digital conversion and high-speed data transmission with low power consumption at high baseband operating frequency. Beyond that, expensive digital signal processing (DSP) and memory access are utilized to process the wide baseband signal, which results intensive computation effort, high power consumption, and potential data damage in parallel computation. To assist DSP, RF/analog signal processing has been attracting great interest in recent [1] - [2], where the signal is manipulated directly in its pristine analog RF waveform domain and in real - time to achieve mathematical operations, such as integrators [3], differentiators [4], Fourier transformers [5], and Hilbert transformers [6] - [8] etc.

To realize dynamic spectrum management in emerging wideband wireless communication, several sensing and detection approaches such as matched filter [9], cyclo - stationary feature detection [10], and wavelet-based edge detection [11] are commonly applied to boost SNR. Hilbert transformer-based edge detection approach has been proposed in digital domain to achieve higher spectrum estimation efficiency and lower computation complexity as in [12] - [13]. In recent, the edge detector working at high frequency has been proposed to sense envelope edge in its analog domain without requiring analog-to-digital converter [14] - [16]. However, the current RF edge detectors are operating at single frequency point with narrow bandwidth, and nontransferable synthesis is needed for frequency upscaling.

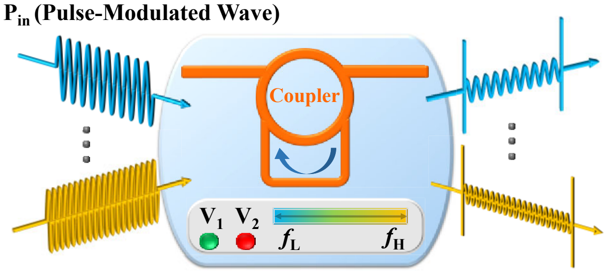

Fig. 1 Schematic diagram of proposed frequency-reconfigurable RF edge detector with two - channel DC control.

In this paper, to overcome the challenges of conventional edge detectors, a novel microstrip line RF tunable edge detector (TED) is proposed to sense the wideband RF modulated signals in real time directly at its analog waveform. Fig.1 shows the circuit topology of proposed RF TED. To be specific, in section II, theoretical analysis is carried out for proposed RF TED, and its frequency reconfiguration characteristic is discussed. In section III, a prototype of proposed frequency reconfigurable RF edge detector operating from 1.9 GHz to 2.4 GHz is designed, and corresponding simulation and measurement are correlated with pulse-modulated signal. The conclusion and future work are discussed in section IV.

II. Design of RF Tunable Edge Detector

A. Design Theory of RF Edge detector

As in Fig. 1, to sense edge of modulated pulse signal, let's assume a pulse-modulated wave $y(t)$ can be mathematically expressed as:

$$y(t) = x_0(t) \cdot x_c(t) \tag{1}$$

Here $x_0(t)$ is the pulse wave with normalized amplitude, duty cycle d and fundamental frequency ω_0.

$$x_0(t) = d + \frac{2}{\pi} \cdot \sum_{n=1}^{\infty} \left(c_n \cdot \cos n\omega_0 t \right) \tag{2}$$

In which $c_n = d \cdot [\sin(\pi n d)/\pi n d]$ is the Fourier expansion coefficient. The term $x_c(t) = \cos(\omega_c t)$ denotes the carrier signal with frequency ω_c. From equation (2), the equation (1) can be expanded in form of the modulation signal with infinite harmonic components around center frequency ω_c.

$$\begin{aligned} y(t) &= (d + \frac{2}{\pi} \cdot \sum_{n=1}^{\infty} c_n \cdot \cos n\omega_0 t) \cdot \cos \omega_c t \\ &= d \cdot \cos \omega_c t + \frac{2}{\pi} \cdot \sum_{n=1}^{\infty} \frac{c_n}{2} \cdot [\cos(\omega_c - n\omega_0)t + \cos(\omega_c + n\omega_0)t] \end{aligned} \tag{3}$$

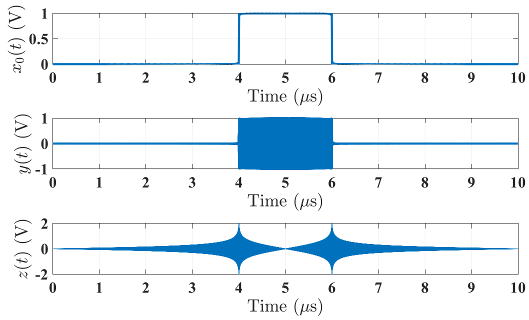

Fig. 2 Pulse-modulated signal with edge detection: pulse width = 2μs, carrier frequency = 2GHz.

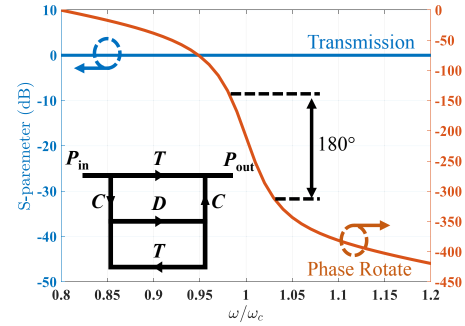

Fig. 3 RF/microwave edge detector: Signal flowchart and frequency response with coupling coefficient $|C| = 0.707$.

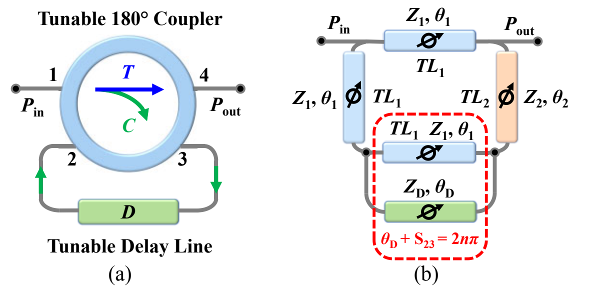

Fig. 4 Proposed tunable RF/microwave edge detector: (a) Coupler-resonator based circuit topology (b) Schematic diagram of equivalent circuit.

Here n is the integer denoting the order of carrier harmonic terms, and frequency deviation ($\omega_c - n\omega_0$ and $\omega_c + n\omega_0$) terms have amplitude attenuation coefficient n, which indicates that higher-order harmonic terms show small contribution. In frequency domain, the equation (3) can be expressed as

$$Y(\omega) = Y_1(\omega - \omega_c) + Y_2[\omega - (\omega_c - n\omega_0)] + Y_2[\omega - (\omega_c + n\omega_0)] \quad (4)$$

Where Y_1 and Y_2 denote the 1st and 2nd term of equation (3).

To sense the edge of modulated signal in its real time RF waveform, from equation (4), the carrier frequency and its higher order harmonic should be suppressed while keeping the fundamental frequency of pulse wave. One approach is to superpose the signal with its out-of-phase version, which can be achieved through the function $H(\omega)$

$$H(\omega) = -j\,\mathrm{sgn}(\omega_c) \quad (5)$$

Such that the output signal z(t) can be expressed as

$$z(t) = F^{-1}[Y(\omega) \cdot H(\omega)] \quad (6)$$

Where sgn(ω_c) is sign function and F^{-1} stands for inverse Fourier transform.

Fig. 2 shows the results of RF edge detection for input pulse-modulated wave, where the pulse width is 2μs and carrier frequency is 2GHz. It is observed from bottom sub-figure that the envelope edge of modulation signal is detected the carrier components are mutually cancelled.

B. Microwave Circuit Implementation

As in Fig. 1, our proposed frequency reconfigurable RF edge detector is composed of coupler and delay line, and the closed-loop structure will resonate at desired operating frequency. The signal flow chart of proposed topology is shown in Fig. 3. Following flowchart rules [17], the transfer function of proposed circuit topology is derived as:

$$S_{in,out}(\omega) = T + \frac{C^2 D}{1 - T \cdot D} \quad (7)$$

The response of this transfer function is also shown in Fig. 3, where the magnitude is uniform in all frequency band, and the phase rotates 180° at center frequency.

To tune the phase rotation frequency, both coupler and feedback delay line are re-designed to resonate at all the frequency in wide tunning range. The tunable transmission line in [18] - [19] is applied to realize microstrip line tunable 180° coupler and tunable feedback delay line, where the characteristic impedance and electrical length of all transmission lines are controlled by external two-channel voltage. Fig. 4 (a) shows the circuit topology of proposed RF TED, where it is composed of tunable 180° coupler and tunable delay line to generate resonance continuously in wide frequency tunning range. Fig. 4 (b) shows the schematic of proposed tunable RF edge detector. Three tunable transmission lines in 180° coupler are note as TL_1 with characteristic impedance of Z_1 and electrical length θ_1. Another tunable transmission line in 180° coupler is noted as TL_2 with characteristic impedance Z_2 and electrical length θ_2, respectively. The delay line, in resonating feedback loop, is designed to meet two requirements within frequency tuning range: 1) the ports input impedance of delay line must be equal to characteristic impedance of the tunable delay line Z_D so that it can always match with other transmission line characteristic impedance in 180° coupler. 2) The electrical length of tunable delay line θ_D must satisfy the condition:

$$\theta_D + \angle S_{23} = 2n\pi \quad (4)$$

where $\angle S_{23}$ denotes the phase delay of the TL_1 between port 2 and port 3 in circuit shown in Fig. 4. Equation (4) indicates the closed loop shown in Fig. 4 (a) which performs as a resonator with total phase delay of $2n\pi$. Here n is any integer. More specifically, a variable capacitor (varactor) is applied to configure both coupler and the delay line operating wide frequency tunning range.

III. Experimental Results and Analysis

To prove our proposed design concept, a microstrip line-based RF tunable edge detector is designed and fabricated on

FR-4 PCB ($\varepsilon_r = 4.5$, $\tan\delta = 0.02$) with thickness of 1.2mm. The size of fabricated circuit is 65 × 60 mm, and the prototype is shown in Fig. 5. The varactor (SMV2020-079LF) is applied in our prototype to meet design requirement for tunable coupler and feedback delay line, and RF choke and DC block are designed to tune the varactors.

A. Validation of Frequency Reconfigurable Edge Detector

The EM simulation and measurement of proposed microwave tunable edge detector are shown in Fig. 6. Both magnitude and phase responses are plotted from 1.9 GHz to 2.4 GHz with 100 MHz steps by tuning two-channel DC control which prove frequency tunning characteristic of proposed RF edge detector. Aligning with theory analysis, the phase rotates 180° at designed frequency, and the passband is on two side of central frequency. Specifically, as in Fig. 6 (a), both $|S_{11}|$ and $|S_{22}|$ are better than 10dB, meanwhile the $|S_{21}|$ is around 2dB in passbands shown in Fig. 6 (b) (the notch is caused from loss such as dielectric loss and conductor loss etc.) In addition, in the phase responses of proposed RF edge detector, the fast phase rotation of 180° between lower side band (LSB) and higher side band (HSB) is obtained at each desired tuning central frequency. The slight distortion of frequency response at f_L (low-end frequency) and f_H (high-end frequency) mainly attributes to the narrow bandwidth of 180° coupler in this design. Also, the deviation of fabrication tolerance, components model, and high dielectric loss from PCB would cause slight frequency shift and extra loss. The comparison of edge detector is shown in Table 1, which highlighted the wide operation bandwidth and reconfigurability of proposed design.

B. Edge Detection for Wideband Modulated Signal

To validate the edge detection function of proposed RF TED, the experiment set up is shown in Fig. 5 (b). The pulse-modulated signal with different carrier frequencies (f_c) is generated from Keysight signal generator (N5172B) and applied to the proposed RF TED. The output signal is observed using high-speed oscilloscope (MSO-S 804A). Fig. 7 and Fig. 8 show the simulation and measurement results of edge detection for pulse-modulated signal with fundamental period of 2μs. Here, the carrier frequency of signal varies from 1.9GHz to 2.4GHz. As seen from red lines, it clearly indicates the edge of pulse-modulated signal at different frequency. The magnitude variation of measured edge at different carrier frequencies are from non-uniform 180° phase rotates at corresponding central frequency, which can be improved by extending bandwidth of 180° coupler in circuit topology.

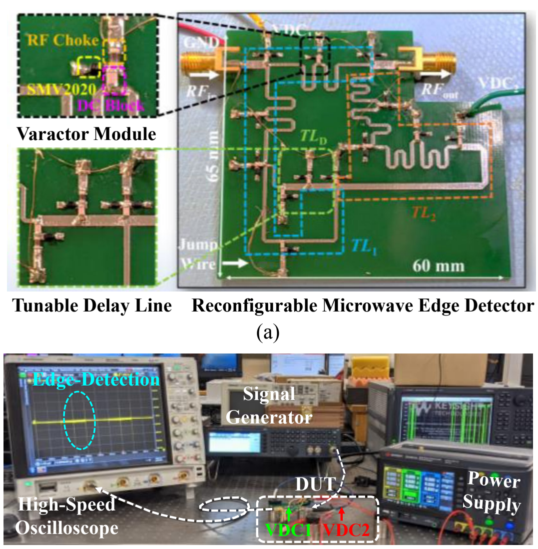

Fig. 5 Experiment of proposed reconfigurable microwave edge detector (a) Fabricated circuit with details (b) Measurement setup with two-channel bias voltage: circuit testbed, DC power supply, signal generator and oscilloscope.

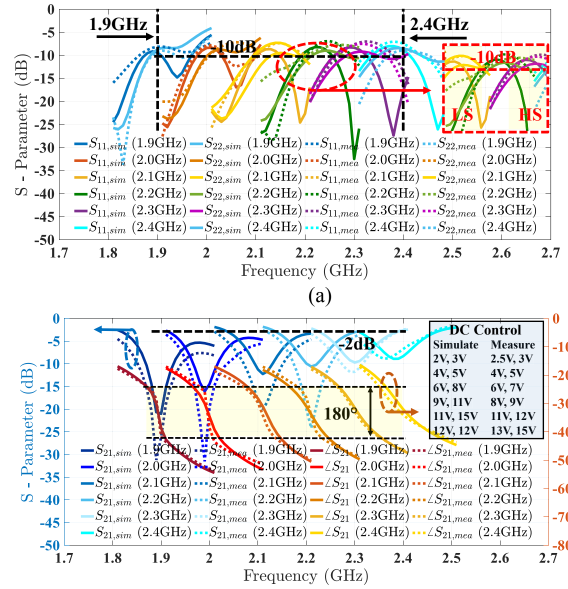

Fig. 6 Experimental results of proposed reconfigurable microwave edge detector (a) Magnitude response: S_{11} & S_{22} (b) Transmission (S_{21}) and phase response ($\angle S_{21}$).

Table 1. Comparison of edge detector

Ref.	Spectrum	Reconfigurable	FBW	Approach
[12]	IF	Yes	N.A	Digital
[14]	RF	No	< 10%	Analog
[15]	RF	No	< 10%	Analog
This work	RF	Yes	23.2%	Analog

IV. CONCLUSION

In this paper, a novel frequency reconfigurable RF edge detector is proposed for real-time RF signal processing. The RF TED circuit is composed of a tunable 180° hybrid coupler and a tunable delay line forming closed-loop resonator. By controlling two-channel voltage, our proposed RF edge detector can sense the edge of pulse-modulated signal with carrier frequency tunning from 1.9 GHz to 2.4 GHz. To verify our design concept, a prototype is designed, fabricated, and validated in experiment, where the measurement results agree well with EM simulation results. Additionally, the edge detection is validated by applying pulse-modulated signal with different carrier frequencies, and it shows clear envelop edges at different frequencies.

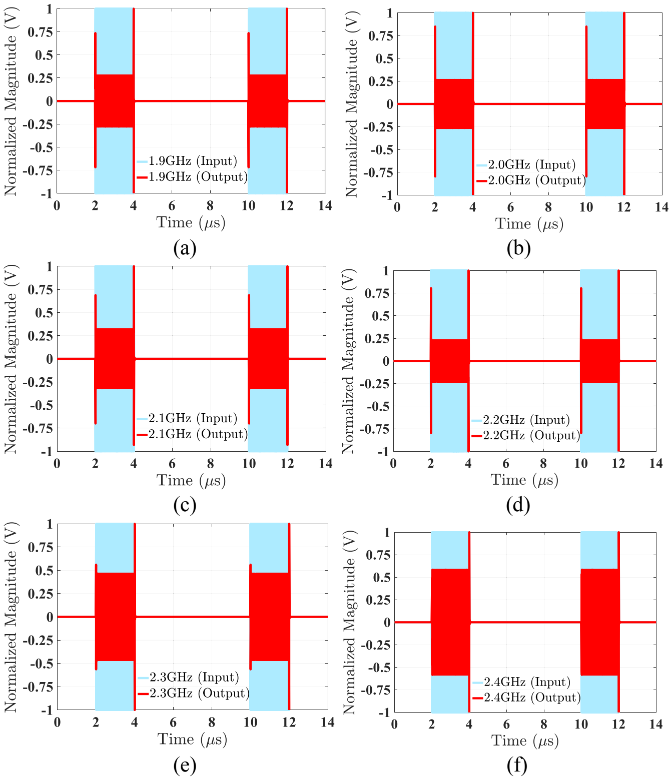

Fig. 7 Simulation results for pulse-modulated input wave whose fundamental period is 2μs with different carrier frequencies f_c and corresponding output waves (a) f_c = 1.9 GHz (b) f_c = 2.0 GHz (c) f_c = 2.1 GHz (d) f_c = 2.2 GHz (e) f_c = 2.3 GHz (f) f_c = 2.4 GHz.

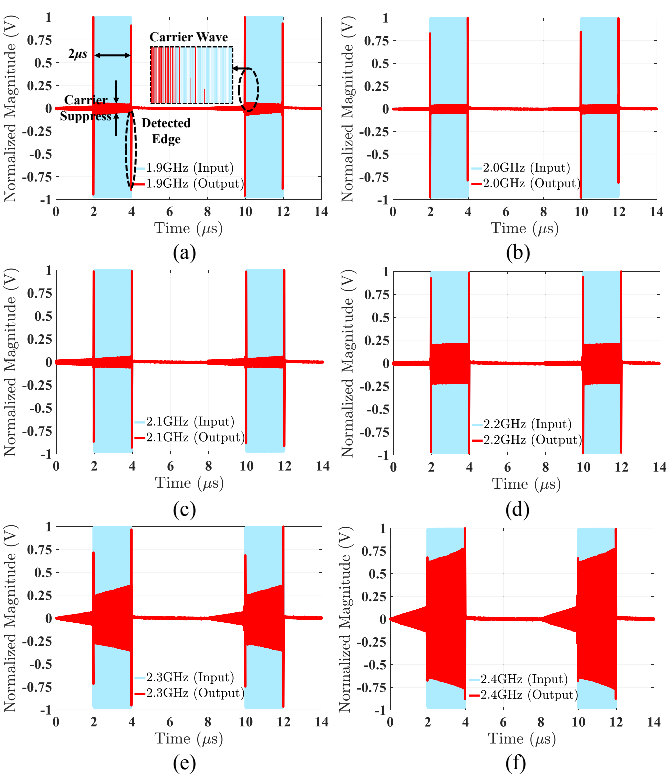

Fig. 8 Measurement results for pulse-modulated input wave whose fundamental period is 2μs with different carrier frequencies f_c and corresponding output waves (a) f_c = 1.9 GHz (b) f_c = 2.0 GHz (c) f_c = 2.1 GHz (d) f_c = 2.2 GHz (e) f_c = 2.3 GHz (f) f_c = 2.4 GHz.

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