The design of wideband leakage canceller for FMCW radars

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ABSTRACT

The Frequency Modulated Continuous Wave (FMCW) radar is widely applied in various fields such as military, transportation, and aviation. However, in an FMCW radar system that uses a single antenna for both transmission and reception, leakage signals from the transmitter can enter the receiver due to the imperfect isolation of the circulator and the impedance mismatch of the antenna. This issue can degrade system performance, distort the reflected signal from the target, and affect the detection capability of small targets in close range. This paper proposes an effective wideband leakage cancellation method utilizing an RF-domain canceller structure combined with a discrete phase control mechanism for narrow sub-bands. The system is designed to automatically adjust the phase shift to effectively cancel the leakage signal across the entire frequency band. Simulation results on ADS Keysight software demonstrate that the proposed leakage canceller achieves over 40 dB cancellation within a 500 MHz bandwidth, which is 4.5 times higher than the conventional method.

Keywords: Continuous Wave Radar; Frequency Modulated Continuous Wave; Leakage Cancellation; Self-Interference Cancellation; Wideband.

1. INTRODUCTION

Frequency-Modulated Continuous-Wave (FMCW) radar has been extensively employed in various modern applications, including military, transportation, mining, and meteorology [1]. Unlike pulsed radar systems, FMCW radar continuously transmits and simultaneously receives reflected signals. Consequently, a significant challenge in the design of such radar systems lies in mitigating the leakage of the transmitted signal into the receiver path due to the limited isolation between the transmission and reception channels.

One approach to enhancing transmission-reception isolation involves the use of separate antennas for the transmitter and receiver. However, in many practical implementations, constraints related to size and system design necessitate the use of a single shared antenna. In such configurations, circulators are commonly employed to separate the received signal from the transmitted signal (figure 1). The transmitted signal propagates from port 1 to port 2 of the circulator and subsequently reaches the antenna. The received signal from the antenna then travels from port 2 to port 3. Ideally, ports 1 and 3 should be completely isolated. However, in practice, circulators exhibit imperfect isolation (typically in the range of 15 to 25 dB). Additionally, impedance mismatches at the antenna further contribute to signal leakage from the transmission path into the reception path.

The presence of leakage signals adversely impacts radar performance by potentially saturating the receiver and distorting the reflected signals from targets, thereby degrading the system’s ability to detect small targets, particularly in the near-field region. To address this issue, various leakage cancellation techniques have been proposed. The effectiveness of a leakage cancellation circuit must be maintained across the entire operational bandwidth of the radar. Since radar range resolution is directly dependent on signal bandwidth, applications requiring high-resolution range measurements, such as drone detection radar, automotive radar, and collision avoidance radar, typically operate over wide bandwidths. Consequently, leakage cancellation circuits designed for such radar systems must also exhibit wideband performance to ensure optimal system operation.

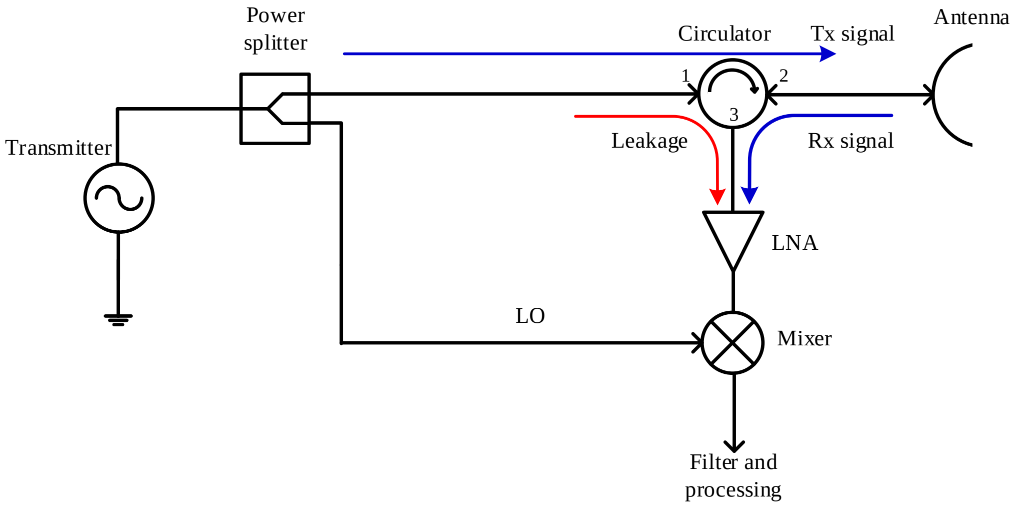


Figure 1. *Block diagram of a single antenna FMCW radar.*

Previously published works have explored passive leakage cancellation techniques [2–5]; however, these methods are predominantly designed for narrowband systems. Similarly, studies on active leakage cancellation, as discussed in [6, 7], have been limited to narrowband continuous-wave (CW) radar applications. The work presented in [8] introduces a leakage cancellation circuit for UHF RFID, though it achieves a bandwidth of only 20 MHz. In [9], a wideband RF leakage cancellation technique employing a filter-based finite impulse response (FIR) modelling approach is proposed, attaining a cancellation level of 21 dB across a 35 MHz bandwidth. Meanwhile, [10] reports on a leakage cancellation circuit designed for X-band FMCW radar, which utilizes phase shifter adjustments to achieve 40 dB suppression within a 600 MHz bandwidth (corresponding to 6% of the center frequency). Several studies have also demonstrated the feasibility of wideband leakage cancellation by employing balanced structures [11–13]; however, these designs are constrained by their susceptibility to antenna impedance mismatches.

This paper proposes an advanced wideband leakage cancellation technique tailored for single-antenna FMCW radar systems. The proposed approach leverages an RF-domain cancellation architecture in which the broad operational bandwidth of the FMCW radar is subdivided into multiple narrow frequency bands. A discrete phase shifter controller is incorporated, wherein each sub-band is assigned a distinct phase shift to compensate for frequency-dependent phase variations inherent in the cancellation signal generation process. The efficacy of the proposed method is rigorously evaluated through simulations conducted in ADS Keysight software, demonstrating significant bandwidth extension while ensuring consistently high leakage suppression across the entire operational frequency range.

The remainder of this paper is structured as follows: Section 2 presents the fundamental architecture of conventional leakage cancellation circuits, along with an analysis of key factors influencing their performance and bandwidth limitations. Section 3 introduces the proposed methodology for wideband leakage cancellation and provides a comprehensive evaluation of its effectiveness. Finally, section 4 concludes the study.

2. CONVENTIONAL LEAKAGE CANCELLER

The simplified structure of the leakage cancellation circuit for transmitter leakage suppression in a single-antenna FMCW radar system is illustrated in figure 2. A portion of the transmitted signal is extracted and fed into the cancellation signal generation circuit (C). Meanwhile, the leakage signal (L) propagates from port 1 to port 3 of the circulator, subsequently entering the receiver and potentially causing receiver saturation. The leakage cancellation circuit comprises three primary components: an attenuator, a phase shifter, and a power combiner. The attenuator, together with the phase shifter, generates a cancellation signal C that has the same amplitude as the leakage signal L but a phase difference of 180°. Consequently, when the signals pass through the power combiner, L and C undergo complete destructive interference, effectively cancelling each other out. As a result, only the desired received signal, coming from the antenna and propagating from port 2 to port 3 of the circulator, is delivered to the receiver.

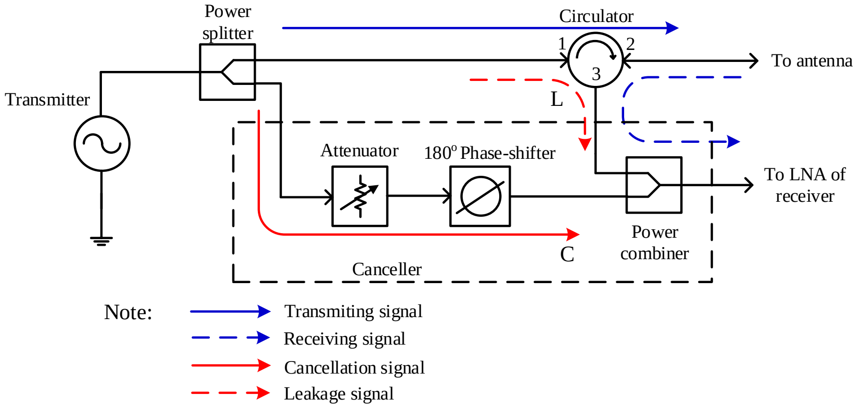


***Figure 2.** Structure diagram of a simple leakage canceller.*

If the components are ideal, their characteristics are independent of frequency, the transmitted leakage signal will be maximally suppressed across the entire operational bandwidth of the radar. Any phase and amplitude mismatch between the leakage signal L and the cancellation signal C will degrade the cancellation performance, with the degree of degradation depending on the magnitude of the mismatch. Here, we consider L as the reference signal, meaning $L = 1$. In this case, $C = \alpha e^{i(\pi+\varphi)}$, where α and φ represent the amplitude and phase deviations. In the ideal case, $\alpha = 1$ and $\varphi = 0$. Thus, the residual signal after cancellation is:

$$R = L + C = 1 + \alpha e^{i(\pi+\varphi)} \tag{1}$$

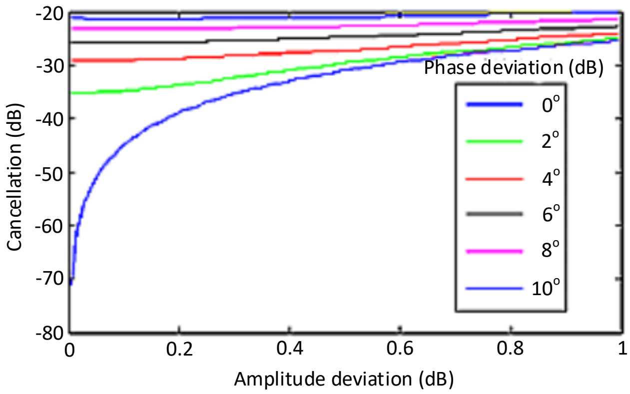


***Figure 3.** The cancellation ratio decreases as the amplitude and phase deviations increase.*

The cancellation ratio is calculated as:

$$I = 10\log_{10}(\frac{R}{L}) = 10\log_{10}(1+\alpha e^{i(\pi+\varphi)}) \tag{2}$$

From equation (2), we can plot the dependence of the cancellation ratio on amplitude and phase deviations, as shown in figure 3. The graph indicates that even small differences in amplitude and phase result in a significant reduction in cancellation efficiency. To achieve a cancellation level of 35 dB or higher, the amplitude and phase deviations must be less than 0.2 dB and 1 degree, respectively.

In practice, the characteristics of all components vary with frequency. As a result, the effectiveness of leakage cancellation is highly dependent on the system's operating frequency, which limits the bandwidth of the leakage cancellation circuit and may prevent it from covering the entire required frequency range.

To investigate this bandwidth limitation further, the following section examines a leakage cancellation circuit using a parametric model of real components, with simulations and evaluations conducted in ADS Keysight. The circuit is designed with a center frequency of 4 GHz. The power splitter/combiner used is the GP2X+ (Minicircuits), which operates over a wide frequency range from 2900 MHz to 6200 MHz; the attenuator is GAT-20+ (Minicircuits) with an operational range from DC to 8000 MHz; the phase shifter is HMC649LP6 (Analog Devices), covering 3000 MHz to 6000 MHz; and the circulator is PE8432 (Pasternack), operating between 2000 MHz and 6000 MHz. All these components exhibit wide operational bandwidths.

Figure 4 illustrates the simulation setup used to evaluate the dependency of amplitude and phase deviations between the leakage signal L and the cancellation signal C as a function of frequency. The results indicate that amplitude deviation shows minimal frequency dependence (figure 5), whereas phase deviation exhibits significant variation across frequencies (figure 6). Consequently, the circuit achieves effective cancellation only within the frequency region where the phase deviation approaches 180°.

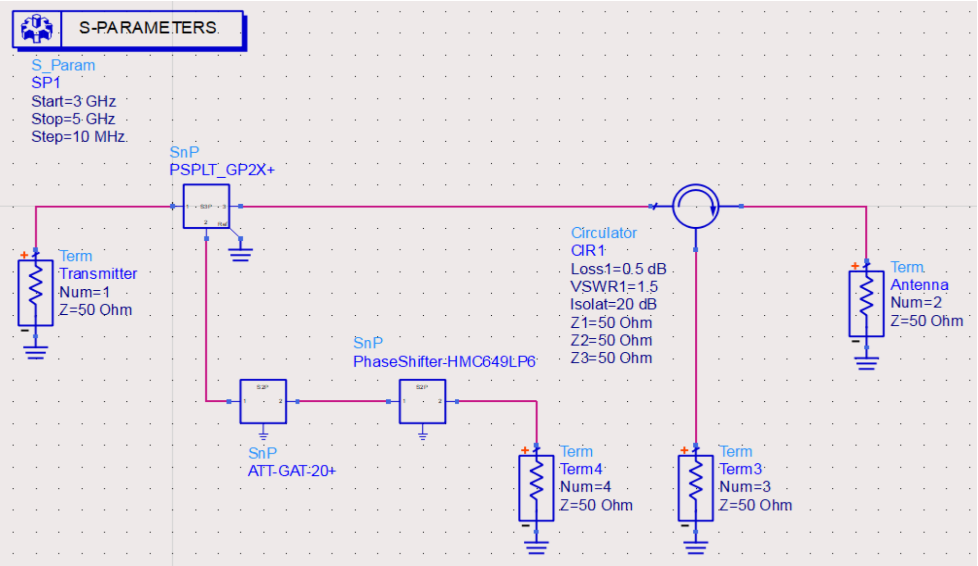


Figure 4. *Investigate the amplitude and phase deviations of L and C with the realistic component models.*

Figure 7 presents the connection diagram used to assess the circuit’s cancellation capability, with Term 3 serving as an observation port for the residual leakage signal after cancellation. The simulation results, shown in figure 8, reveal that despite the wide operational bandwidth of the system components, the circuit maintains a leakage suppression level exceeding 40 dB only within a limited bandwidth of approximately 110 MHz. For high-resolution FMCW radar applications, further bandwidth expansion is necessary to meet performance requirements.

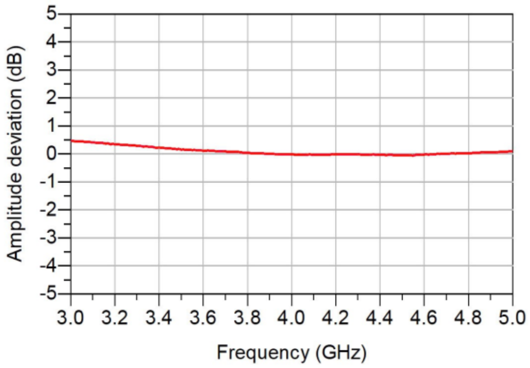


Figure 5. *Amplitude deviation vs frequency.*

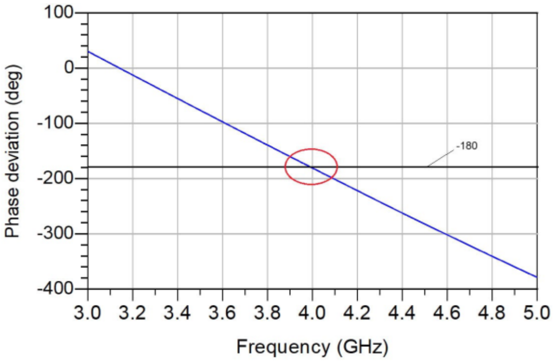


Figure 6. *Phase deviation vs frequency.*

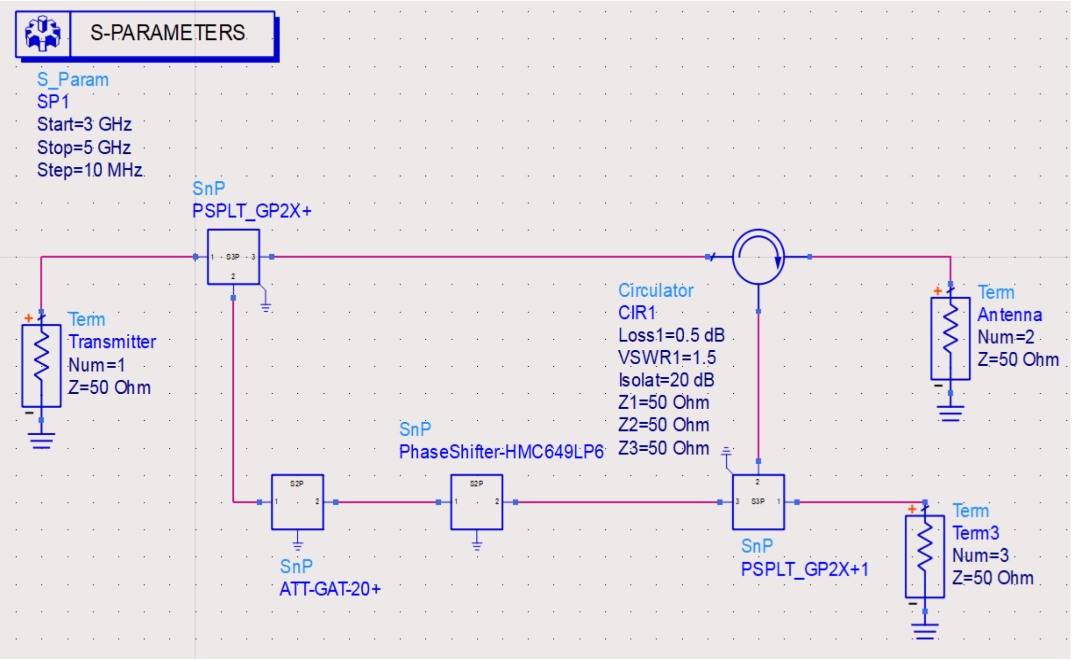


Figure 7. *Simulation diagram of the leakage cancellation circuit with a realistic component model.*

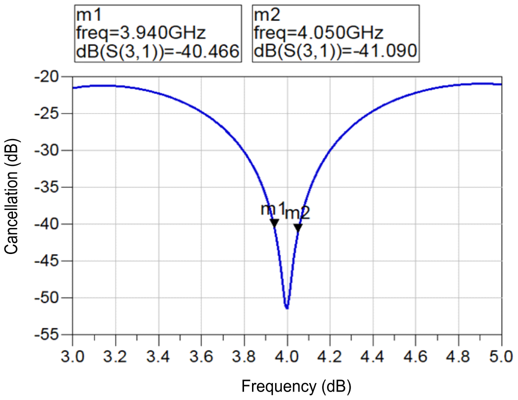


Figure 8. *Cancellation vs frequency.*

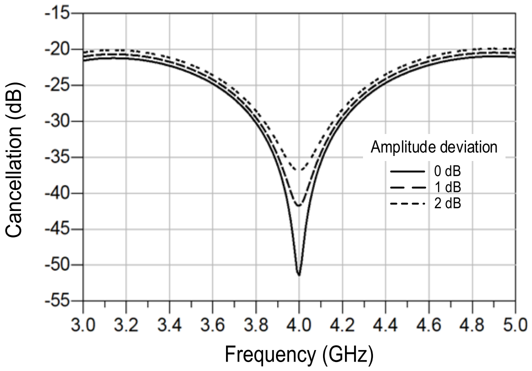


Figure 9. *Cancellation characteristic with differrent amplitude deviations.*

Next, we perform a parameter sweep of the attenuation and phase shift to evaluate the impact of amplitude and phase deviations on the leakage cancellation ratio. The results are presented in figures 9 and 10. From figure 9, it can be observed that amplitude deviation reduces the cancellation ratio but does not affect the frequency range of the circuit. In contrast, variations in phase deviation significantly shift the operating frequency (figure 10). This implies that for each specific phase shift value, the circuit achieves optimal leakage cancellation performance within a certain frequency range. These results are fully consistent with the analysis presented in figures 5 and 6.

Based on the above results, combined with the characteristics of FMCW radar signals, we will design a wideband leakage cancellation circuit and evaluate its performance in the following section.

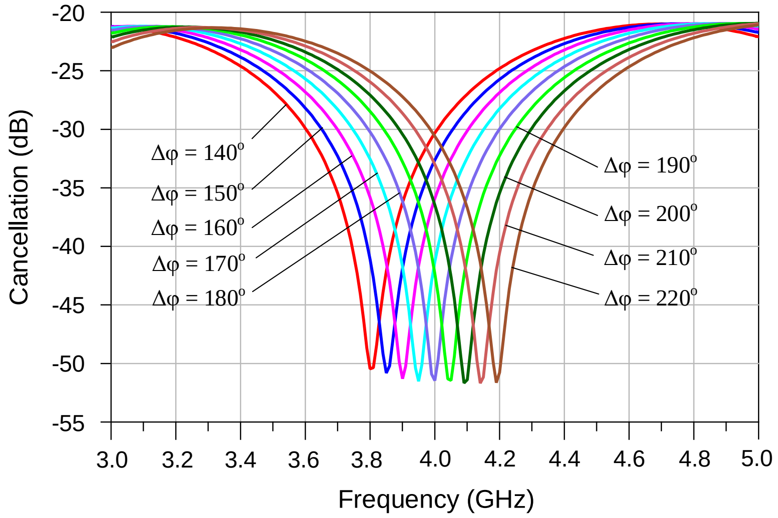


Figure 10. *Cancellation characteristics with different phase shifts.*

3. DESIGN OF WIDEBAND LEAKAGE CANCELLER

The FMCW signal exhibits a linearly varying frequency over time. The entire signal bandwidth can be divided into smaller frequency segments, with each segment corresponding to a specific time interval within each signal cycle (figure 11). Building upon the results in figure 10, we design a wideband leakage cancellation circuit consisting of an attenuator, a controllable phase shifter, and a timing-synchronized controller. This controller adjusts the phase shift according to the corresponding time intervals. The proposed leakage cancellation circuit for FMCW radar is designed to operate at a center frequency of 4 GHz, with a relative bandwidth exceeding 10% of the center frequency. The block diagram of the leakage cancellation circuit is shown in figure 12. Based on the analysis in figure 10, a table mapping phase shift values to time and frequency is constructed, as presented in table 1.

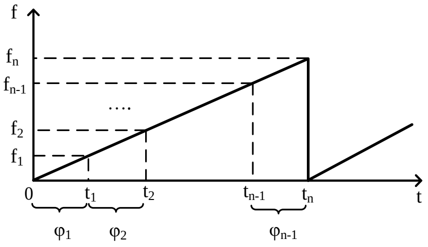


Figure 11. *Dividing the bandwidth into n segments.*

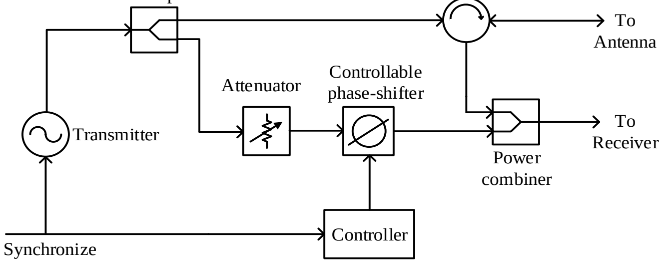
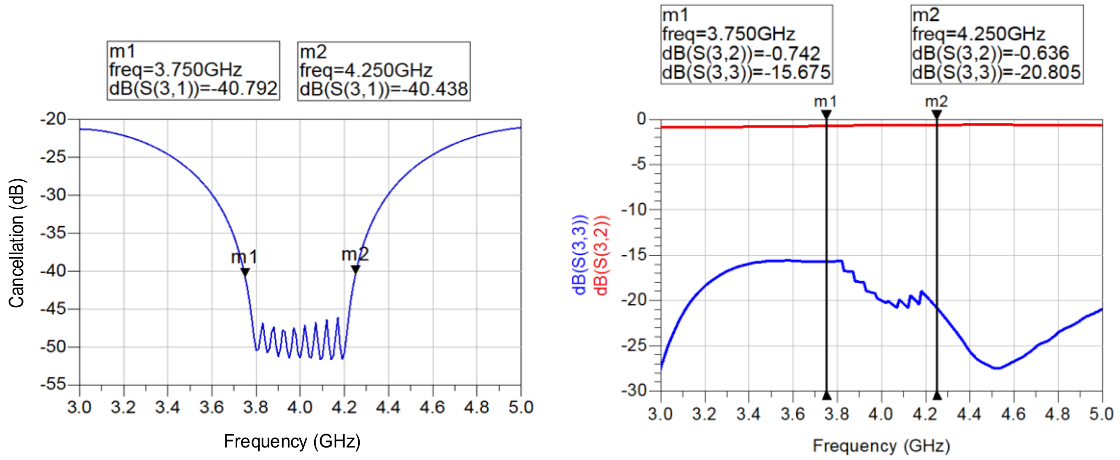


Figure 12. *Block diagram of the proposed wideband leakage canceller.*

Table 1. *Phase shift corresponding to time and frequency.*

No.	Time	Freq (GHz)	Phase shift (deg)
1	0 - t_1	< 3.83	140
2	t_1 - t_2	3.83 - 3.88	150
3	t_2 - t_3	3.88 - 3.93	160
4	t_3 - t_4	3.93 – 3.98	170
5	t_4 - t_5	3.98 – 4.03	180
6	t_5 - t_6	4.03 – 4.08	190
7	t_6 - t_7	4.08 – 4.13	200
8	t_7 - t_8	4.13 – 4.18	210
9	t_8 - t_9	> 4.23	220

The simulation results of the proposed wideband leakage canceller in ADS, using the same real components as in section 2, are shown in figure 13. The proposed circuit achieves a leakage cancellation ratio of over 40 dB within the frequency range of 3.75 GHz to 4.25 GHz, corresponding to a bandwidth of 500 MHz (12.5% of the center frequency). This bandwidth is 4.5 times greater than that of the conventional cancellation circuit in section 2, with the same trade-off in transmission and reception signal losses due to their identical signal paths. Table 2 presents a performance comparison between the proposed leakage canceller and other published works. The results indicate that the proposed circuit achieves a significantly wider bandwidth compared to existing solutions.



a) b)

Figure 13. *Simulation result in ADS: a) Cancellation ratio; b) Insertion loss and reflection of the receive path.*

Table 2. *Performance comparison.*

Work, published year	[14], 2016	[15], 2019	[16], 2019	[10], 2021	**This work**
Frequency (GHz)	4.3	2.4	4.5	10	**4**
Relative bandwidth (%) with cancellation > 40 dB	2.3	3.33	3.33	6	**12.5**
Structure	Impedance mismatch terminal	Balanced	Quasi-circulator	Balanced	**Discrete phase shift**

4. CONCLUSIONS

This paper has presented an efficient design methodology for a wideband leakage canceller in single-antenna FMCW radars, utilizing a discrete phase control mechanism to optimize leakage suppression across narrow frequency bands. Simulation results demonstrate that the proposed approach significantly enhances the cancellation bandwidth, meeting the requirements of high-resolution FMCW radar systems.

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TÓM TẮT

Thiết kế bộ khử tín hiệu rò dải rộng cho ra đa FMCW

Ra đa điều tần tuyến tính liên tục (FMCW) được ứng dụng rộng rãi trong nhiều lĩnh vực như quân sự, giao thông và hàng không. Tuy nhiên, trong hệ thống ra đa FMCW sử dụng một ăng ten chung cho cả phát và thu, tín hiệu từ tuyến phát có thể rò rỉ vào tuyến thu do sự cách ly không hoàn hảo của circulator và sự mất phối hợp trở kháng của ăng ten. Điều này có thể làm giảm hiệu suất hệ thống, gây méo tín hiệu phản xạ từ mục tiêu và ảnh hưởng đến khả năng phát hiện mục tiêu nhỏ ở vùng gần. Bài báo đề xuất một phương pháp khử tín hiệu rò dải rộng hiệu quả, sử dụng cấu trúc bộ khử tín hiệu rò ở tần số RF kết hợp với bộ điều khiển dịch pha rời rạc theo từng băng tần hẹp. Hệ thống được thiết kế để tự động điều chỉnh độ dịch pha nhằm bù khử hiệu quả tín hiệu rò trong toàn bộ dải tần. Kết quả mô phỏng trên phần mềm ADS Keysight cho thấy bộ khử tín hiệu rò đề xuất đạt hệ số khử trên 40 dB trong dải thông 500 MHz, gấp 4,5 lần so với phương pháp truyền thống.

Từ khóa: Ra đa sóng liên tục; Điều tần tuyến tính liên tục; Khử tín hiệu rò; Khử nhiễu nội tại; Dải rộng.