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2.45 GHz Active Isolator based on asymmetric coupler

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ABSTRACT
An active isolator achieving both high isolation and low insertion loss at 2.45 GHz is proposed. The isolator is based on an asymmetric coupler and is designed to leverage the gain and reverse isolation of an amplifier and coupling coefficients between the input and output of the coupler. The insertion loss and isolation of the isolator are enhanced by using the coefficients, and the power level with optimal isolation can be determined for a target specification. The asymmetric coupler increases the power handling capability of the proposed isolator that has a low coupling coefficient and achieves highly efficient isolation with a high coupling coefficient. Electromagnetic-circuit co-simulation results show that the proposed isolator with operation stability has ≥ 40 dB isolation and < 1 dB insertion loss for input power between 0–8 dBm.

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KEYWORDS
Active isolator; asymmetric coupler; amplifier; high isolation; optimum design methodology

1. Introduction

A microwave isolator is a two-port device with unidirectional transmission characteristics such that signal transmission occurs in only one direction at the matched ports [1]. The isolator is useful for preventing possible damage from reverse transmission in RF/microwave systems and measurement equipment [2]. Ferrite-based isolators are conventionally used in such systems, however, the isolators are bulky, heavy, and expensive, thereby causing them to be poorly suited for use in multiple applications [3]. Magnetic-free isolators based on resonators or varactors have been studied as a substitute to ferrite-based isolators, however, they also have limited applications because of their low isolation and low power handling capability [4].

An active isolator based on an amplifier with non-reciprocal characteristics has been presented as a magnetic-free isolator in several studies [5–8]. An active isolator can be implemented with a small volume and low weight to achieve high isolation and low insertion loss simultaneously [9]. However, active isolators have a few drawbacks: power consumption to drive the device and the need for interconnections for supply of the bias voltages [10]. Furthermore, there exist three disadvantages that arise from specific characteristics of the active components of active isolators and these should be considered in prospective applications. First, the frequency bandwidth of the active isolator indicating high isolation is narrower than that of a passive isolator because the isolation is obtained by signal cancellation in a narrow frequency band between in-phase and out-of-phase signals at the output [11]. The isolator components can be designed such that the operating bandwidth meets the application requirements. Secondly, as active components exhibit non-reciprocity over a limited and fixed range of input signal power, there is a limit to the amount of high input power transmission that the isolator can handle [12]. Thirdly, a high-gain amplifier for high isolation can increase the instability and power consumption of the isolator [13]. Active isolators based on a symmetric hybrid coupler and an amplifier with less than unit voltage gain have been proposed for high isolation with the decrease of both the instability and the power consumption. However, the power handling capability of the isolator cannot be improved because of the power limit at the input of the amplifier [14].

In this paper, an active isolator with high isolation and low insertion loss is proposed by using an asymmetric coupler that implements different coupling coefficients between the input and output ports. The coupling coefficients are obtained by asymmetric characteristic impedances and the reflection coefficient to compensate for the mismatch from the asymmetricity [15]. The input power range with high effective isolation can be increased by adjusting the coupling ratio between the input and output ports. The proposed isolator using the amplifier with a gain of 1.1 is demonstrated to simultaneously achieve high isolation, high stability, and low insertion loss at 2.45 GHz by electromagnetic (EM)-circuit co-simulation.

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2. Design methodology

The proposed active isolator consists of a common-source (CS) amplifier with a half wave of phase difference between the input and output and an asymmetric coupler as shown in Figure 1. When three ports of the proposed asymmetric coupler are perfectly matched to the reference impedance of 50 Ω, the S-parameter matrix of the asymmetric hybrid coupler can be expressed using its reciprocal property in [15] as:

$$[S] = \begin{bmatrix} 0 & S_{12} & S_{13} & S_{14} \\ S_{21} & 0 & S_{23} & S_{24} \\ S_{31} & S_{32} & 0 & S_{34} \\ S_{41} & S_{42} & S_{42} & S_{44} \end{bmatrix} \tag{1}$$

Assuming that each port in the coupler is mutually independent, the relationship between the signals transmitted to the ports 1 and 2 can be obtained from (1) as:

$$S_{13}S_{23}^{*} + S_{14}^{*}S_{24} = 0 \tag{2}$$

To define each coupling coefficient of the asymmetric directional coupler, (2) can be modified to:

$$S_{24} = \frac{-S_{23}^{*}S_{13}}{S_{14}^{*}} \tag{3}$$

Furthermore, $|\alpha|$, which is the ratio of $|S_{23}|$ to $|S_{14}|$, can be derived using

$$\left|\frac{S_{23}^{*}}{S_{14}^{*}}\right| = |\alpha| \tag{4}$$

The coupling coefficient of the proposed isolator can be rewritten from (3) as:

$$|S_{24}| = |S_{13}| \cdot |\alpha| \tag{5}$$

When a transmission coefficient T under lossless condition is assumed, $|S_{21}|$ and $|S_{31}|$ are expressed as:

$$|S_{21}| = T, \tag{6}$$

$$|S_{31}| = \sqrt{1 - T^2}. \tag{7}$$

$|S_{21}|$ shows the power ratio of the signal transmitted directly from the input to the output of the isolator through the coupler. The directly transmitted signal can be cancelled by the out-of-phase signal with the same power level. The out-of-phase of the signal is implemented by the transfer function of the CS amplifier, which has a phase difference of 180° between the input and output ports of the amplifier. The magnitude of the transfer function H_{cancel} of the signal passed through the coupler and the amplifier is expressed as:

$$|H_{cancel}| = |S_{31}||G||S_{24}|, \tag{8}$$

where G is the gain of the CS amplifier that cancels the input signals. To achieve the best isolation performance, the relationship between the signals must meet the following condition

$$|S_{21}| = |S_{31}||G||S_{24}|. \tag{9}$$

As the wave propagates from port 2 to port 1, a small amount of energy must be coupled to the input of the amplifier [16]. However, the output signal of the amplifier must be strongly coupled to port 2 to cancel the applied signal from port 1. Owing to the characteristics of the asymmetric coupler, the ratio of $|S_{31}|$ to $|S_{24}|$ can be adjusted and is defined as

$$|\alpha| = \frac{T}{|G|(1 - T^2)}. \tag{9}$$

As shown in (9), $|\alpha|$ determines the insertion loss and isolation of the proposed isolator. The design conditions in (8) and (9) show that it is possible to achieve high isolation by using the asymmetric characteristics of the coupler and the appropriate gain of the power amplifier. In addition, the power handling capability can be increased in the proposed isolator because the input power of the amplifier can be reduced by the asymmetric coupler while maintaining high isolation.

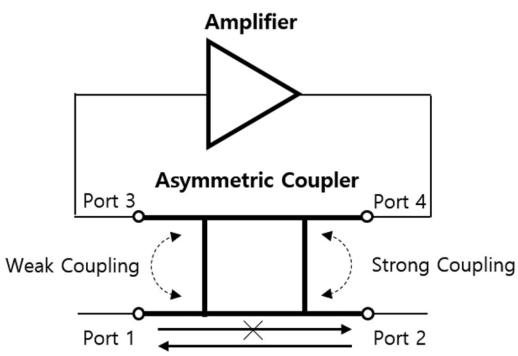

Figure 1. Block diagram of the proposed isolator based on an asymmetric coupler.

3. Amplifier design

The RF amplifier in the proposed isolator provides non-reciprocal characteristics using reverse isolation of the transistor in the amplifier. The RF amplifier is generally designed with the input and output matching condition to the reference impedance of 50 Ω. However, the amplifier in the proposed isolator should be designed with a certain impedance to optimize the performance of the isolator. Port 4 of an asymmetric coupler should be terminated with a certain impedance intentionally mismatched with the reference impedance because of the compensation of the asymmetric coupling coefficient [15]. In the design of the proposed isolator, port 4 of the coupler is designed to be terminated with the impedance of 55 Ω. The magnitude of the reflection coefficient at the output of the amplifier can be increased because the unmatched port 4 of the coupler is connected to the output of the amplifier. This causes

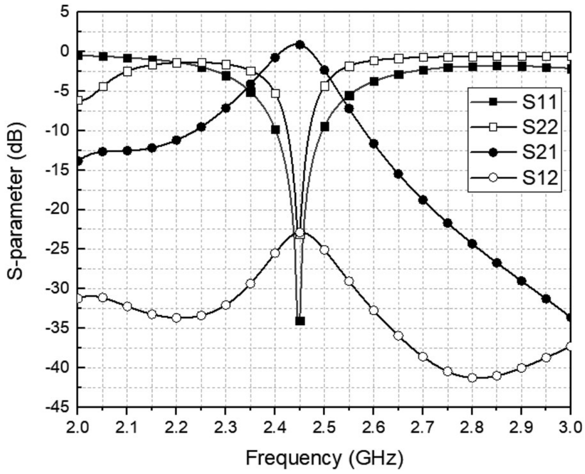

Figure 2. Simulated S-parameters of the amplifier itself in the proposed isolator.

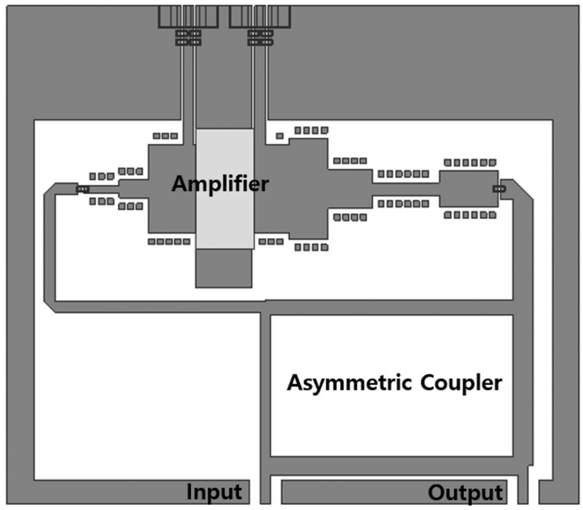

Figure 3. Layout design of the 2.45 GHz isolator on an FR4 printed circuit board.

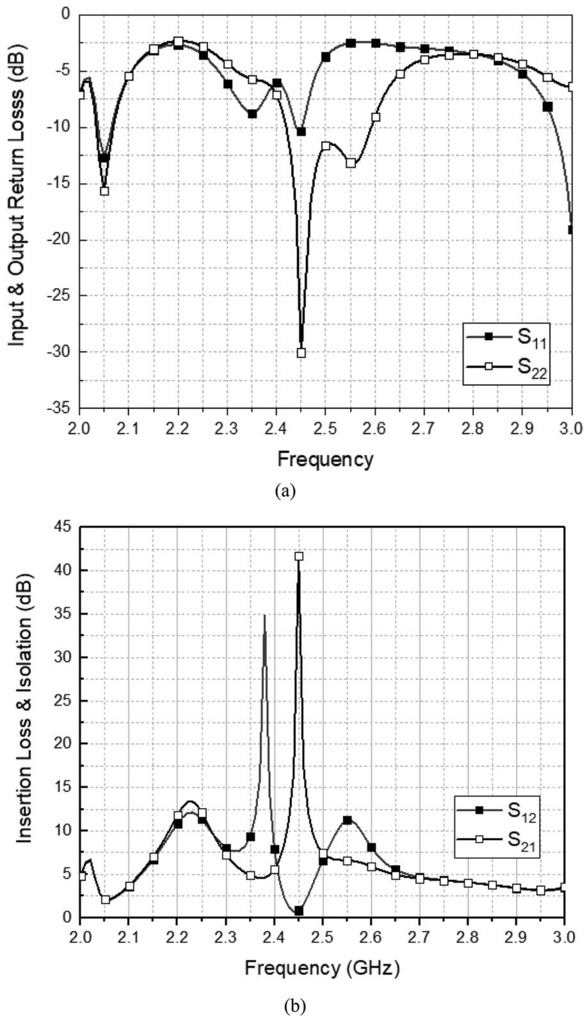

Figure 4. EM-circuit co-simulation results for the proposed isolator: (a) Input ($|S_{11}|$) and output ($|S_{22}|$) return losses; (b) Insertion loss ($|S_{12}|$) and isolation ($|S_{21}|$).

degradation of the performance indicators of the proposed isolator, such as the stability and isolation. Therefore, the output impedance of the amplifier is designed to the impedance of 45 Ω to minimize impedance mismatching between the coupler and amplifier.

The S-parameters of the standalone amplifier shown in Figure 2 are independently simulated without consideration of the characteristics of the coupler of the proposed isolator, however, the reflection coefficient at the output is sufficiently low owing to a small impedance difference between the 45 Ω impedance and the reference. The input and output return losses at the centre frequency of 2.45 GHz are obtained to be −34 dB and −23 dB, respectively. The voltage gain and the reverse isolation are simulated to be 0.89 dB and −22. 9 dB at 2.45 GHz, respectively.

4. Results & discussion

The EM-circuit co-simulation method is a useful method and is commonly used to show accurate circuit characteristics and performances by considering the exact characteristics of RF active and passive devices, both parasitic components and coupling effects in the implementation based on electromagnetic wave analysis [17–22]. Figure 3 presents a layout design with a dimension of 87 × 94 mm^2 for EM-circuit co-simulation using Keysight ADS Momentum. The asymmetric coupler using transmission lines was integrated onto an FR4 substrate. A LDMOS BLC2425M10 240 transistor manufactured by Ampleon was used in the amplifier. The high design accuracy of the amplifier and asymmetric coupler using EM-circuit co-simulation at the operating frequency was verified in the previous studies [14,21]. Figure 4 shows the S-parameter results when the amplifier is biased at the drain voltage of 13.5 V and gate voltage of 1.85 V. The input and output return losses at the operating frequency of 2.45 GHz are simulated to be 10.3 and 30 dB, respectively. The simulation results show maximum isolation of 41.7 dB and insertion loss of 0.84 dB at 2.45 GHz. The bandwidth of the proposed isolator is limited because the coupling coefficients of the asymmetric

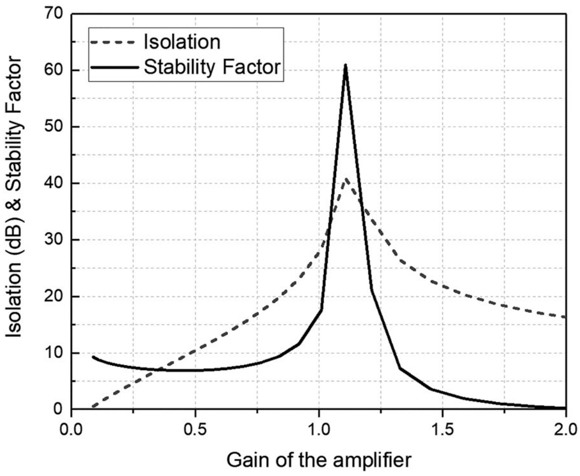

Figure 5. Stability factor and isolation of the proposed isolator as functions of the voltage gain of the amplifier.

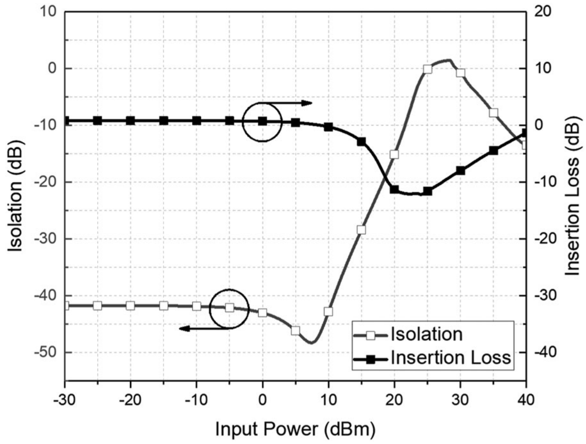

Figure 6. Performances of the 2.45 GHz isolator in large-signal simulation.

coupler and the frequency responses of the amplifier for achieving the isolation characteristic are implemented in a narrow band. The isolation in the active isolator is generally sensitive depending on the gain of the amplifier, and the same characteristic is indicated in the proposed isolator. In addition, when a high-gain amplifier is required for achieving high isolation, the possibility of oscillation in the amplifier can significantly increase. Thus, we must consider the magnitude of dependence of the isolation and stability of the isolator on the gain of the amplifier.

Figure 5 shows the effects of the gain of the amplifier on the isolation and stability of the proposed isolator at 2.45 GHz. The maximum values of the stability factor and isolation are achieved at the gain of 1.1, indicating that the proposed isolator is stable at the highly-isolated condition even though the amplifier gain is greater than one on account of the asymmetric coupling coefficients of the coupler. The results can be also explained by the decrease in the positive feedback to the input of the amplifier due to the high isolation of the proposed isolator. As the gain of the amplifier can be sensitively changed depending on the operating conditions such as the bias voltages and temperature, the requirement of accurate gain in the amplifier may be a disadvantage of the proposed isolator. The proposed isolator maintains isolation of more than 30 dB with a 10% deviation from the optimum gain.

Figure 6 presents the simulated large-signal results for the proposed isolator. The minimum insertion loss is 0.84 dB in the input power range of −30–40 dBm. The proposed isolator at the input power below 0 dBm has high isolation because the magnitude of the signal to be cancelled is small and it is necessary to only consider the amplifier gain at the fundamental frequency. When the input power is larger than 10 dBm, the isolation of the proposed isolator deteriorates regardless of the amplifier gain because the leakage feedback by the reverse isolation of the amplifier itself increases. Compared to the active isolator based on a symmetric coupler, the power handling capability of the proposed isolator can be improved by the weakly coupled signal, which is obtained by using the asymmetric coupler and is transmitted to the input signal of the amplifier. Furthermore, the power handling capability can be tuned by using the gain of the amplifier and the asymmetric coupling coefficients of the coupler. In other words, the performance improvement of the proposed isolator is based on the increase in the degree of freedom in the design by the asymmetric coupling coefficients, compared to the conventional isolator with symmetric coupling coefficients. When a weaker coupling coefficient is designed at the input of the isolator by the asymmetric coupler, the input power of the isolator can increase further to exhibit high isolation. However, the performance improvement is limited by the characteristics of the asymmetric coupler because the asymmetric coupling coefficients of the coupler should be compensated by the output impedance of the amplifier.

Table 1. Comparison of active isolators around 2.45-GHz band.

	[10]	[16]	[22]	This work
Centre Frequency (GHz)	2.7	2.05	2.25	2.45
Insertion Loss (dB)	6.8	1.03	2	0.84
Isolation (dB)	26.8	36.2	> 25	41.7
Effective Isolation (dB)	20	35.17	> 23	40.86
Return Loss (dB)	> 10	> 10	> 10	> 10

A comparison of the proposed isolator with other active isolators is presented in Table 1. Compared to previous studies on active isolators, the proposed active isolator based on the asymmetric coupler exhibits a lower insertion loss and higher isolation in the frequency band of approximately 2 GHz.

5. Conclusion

High isolation and low insertion loss at 2.45 GHz are simultaneously achieved using an active isolator based on an asymmetric hybrid coupler. Owing to compensation for the asymmetric coupling coefficients of the coupler by the gain of the amplifier, the performances of the proposed isolator are enhanced at the operating frequency. A low coupling coefficient of the asymmetric coupler contributes to the increase of the power handling capability of the proposed isolator. The effective isolation, which is the difference between the isolation and the insertion loss, is demonstrated to be 40.86 dB at 2.45 GHz through an EM-circuit co-simulation. The large-signal simulation shows that the optimum input power can be designed using the coefficients of the coupler and the gain of the amplifier.

Disclosure statement

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