2.4-GHz Power Amplifier with Power Detector Using Metamaterial-Based Transformer-Type On-Chip Directional Coupler

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This letter presents a power amplifier (PA) with an on-chip power detector for 2.4-GHz wireless local area network application. The power detector consists of a clamp circuit, a diode detector, and a coupled line directional coupler. A series inductor for an output matching network in the PA is combined with a through line of the coupler, which reduces the coupling level. Therefore, the coupler employs a metamaterial-based transformer configuration to increase coupling. The amount of coupling is increased by 2.5 dB in the 1:1 symmetric transformer structure and by 4.5 dB from two metamaterial units along the coupled line.

Keywords: Power amplifier, power detector, directional coupler, metamaterial, transformer.

I. Introduction

In most modern wireless communication systems, the ability to detect power is a critical part of a transmitter. Therefore, a power detector is commonly included in a power amplifier (PA) module to sense the transmission power level of the PA and convert it into voltage. The power level of the transmitter is monitored and controlled by the output voltage of the power detector.

There are two kinds of power detector. One is an active power detector, and the other is a passive power detector. The former uses transistors for detecting circuitry [1], and the latter uses only passive components, such as diodes, resistors, and capacitors [2], [3]. The active detector is usually employed in a PA implemented in Si technology [1], whereas the passive detector is commonly used in GaAs technology [3]. The active detector responds to a high voltage level by amplification via DC power consumption. The passive detector maintains a low voltage level because it lacks amplification.

One important factor when designing a power detector is the loading effect. If the output impedance of the PA varies, the output voltage of the power detector may change due to reflection. A common way to avoid this loading effect is to incorporate a directional coupler for directivity. However, a coupler in a low frequency application needs to be large enough to enable sufficient coupling, which means that the coupler is usually embedded in a packaging substrate [4]. In this work, a passive power detector with an on-chip coupled line directional coupler is presented. To enhance coupling, a metamaterial-based transformer configuration is employed in the coupler design.

II. Power Amplifier Design with On-Chip Coupler

The PA is implemented in InGaP/GaAs heterojunction bipolar transistor (HBT) technology by using the foundry service of WIN Semiconductors Corporation. The technology code is H02U-32, and the minimum emitter feature size is 2 μm. The two-stage PA design in class AB operation is based

Manuscript received Aug. 13, 2012; revised Sept. 26, 2012; accepted Oct. 4, 2012.

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0009618). This research was supported by Mid-career Researcher Program through the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (2011-0027661). This work was sponsored by the IC Design Education Center (IDEC).

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http://dx.doi.org/10.4218/etrij.13.0212.0350

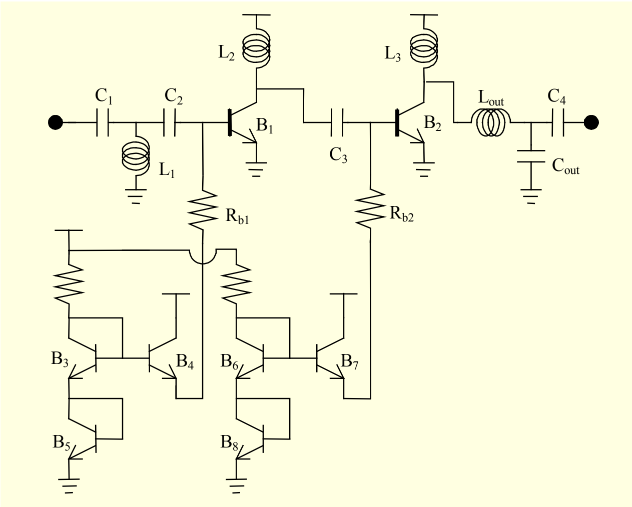

Fig. 1. Simplified PA configuration.

on the configuration in [5]. The major difference is the output matching network, which is co-designed with the on-chip coupler in this work.

A simplified schematic of the PA is shown in Fig. 1. The two-finger HBT with an emitter size of 2 μm × 20 μm is selected as a unit power cell from linearity simulation. The power devices of the driver stage (B_1) and the power stage (B_2) are designed with a parallel combination of four unit cells and 24 unit cells, respectively. Each unit cell includes ballast resistors (R_{b1} and R_{b2}) to avoid thermal runaway [5]. The bias and the RF signal path are separated to preserve gain. The high-pass network is used for input and the inter-stage matching, and the low-pass network is used for output matching. In the scheme, C_1, C_2, and L_1 are designed to bring the input impedance to 50 Ω, and C_3 and L_2 are chosen to make the gain peak at the center of the band and to maintain linearity decided from the power stage design. The output matching network consists of L_3, L_{out}, C_{out}, and C_4. Here, L_3 and C_4 are selected to provide high and low impedance so that L_{out} and C_{out} become dominant for load impedance. The bias circuits are composed of B_3 through B_8, based on current sources with one more diode stack to preserve the base-emitter voltages of the power devices.

Figure 2(a) shows a conventional output stage configuration of a PA, including a coupled line directional coupler for a power detector. The basic directional coupler consists of a through line and a coupled line with a quarter-wave length. Usually, the output matching network of L_{out} and C_{out} is integrated on the chip, and the coupler is implemented in a packaging substrate due to size. Figure 2(b) presents a simplified representation of this work.

The transmission lines of the coupler are integrated on the chip, and the through line is co-designed with L_{out}. Because the

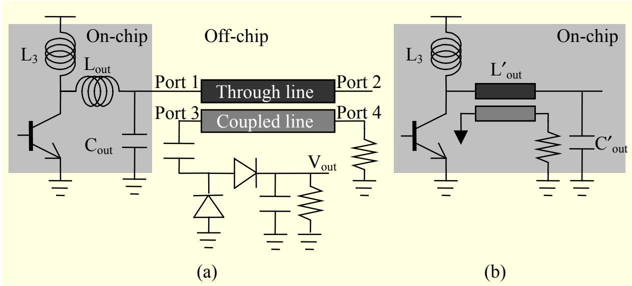

Fig. 2. PA configuration with (a) conventional off-chip coupler and (b) on-chip coupler with output matching network combined.

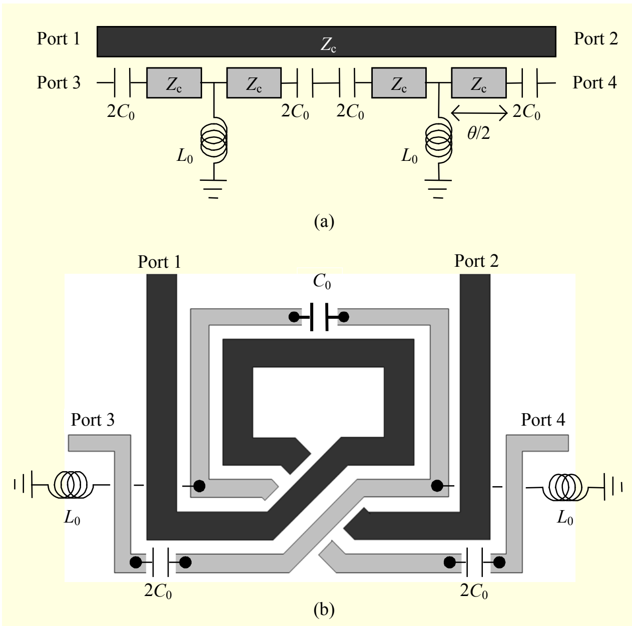

Fig. 3. Structure of (a) regular metamaterial-based coupler and (b) metamaterial-based transformer-type coupler.

length of the through line should be determined by the inductance of L'_{out} required for matching, the on-chip coupler lines are almost ten times shorter than a quarter-wave length. Therefore, the amount of coupling is reduced substantially. In this work, a metamaterial-based transformer configuration is proposed to boost coupling.

In this work, the coupled power from Port 3 is converted into voltage by a common diode detector, as shown in Fig. 2(a). A clamp circuit is used to increase the detecting voltage. The target output voltage of the power detector is 1 V at an output power of 16 dBm. Therefore, the coupler is designed to have a coupling level of –12 dB. However, the short on-chip coupler co-designed with the matching network shows coupling of –19 dB.

Figure 3(a) shows the coupler with two metamaterial unit cells along the coupled line. It has been published that a composite right-/left-hand coupled transmission line not only improves coupling and directivity of a directional coupler [6] but also reduces size [7] in PCB technology. The metamaterial unit is designed by (1), which is the dispersion equation without attenuation. In the low frequency limit ($kd \ll 1$, $\beta d \ll 1$), by using some approximations ($\sin x \approx x$, $\cos x \approx 1$), (1) can be simplified into (2), having two cutoff frequencies (ω_{c1}, ω_{c2}) from each term.

$$\cos h(j\beta d) = \cos\theta - \frac{1}{2\omega^2 L_0 C_0}\cos^2\frac{\theta}{2} + \frac{1}{2\omega}\left(\frac{1}{C_0 Z_c} + \frac{1}{L_0 Y_c}\right)\sin\theta, \quad (1)$$

where the characteristic impedance is $Z_c = \sqrt{L/C}$ and the electrical length is $\theta = kd$.

$$\beta^2 = \left(\omega L d - \frac{1}{\omega C_0}\right)\cdot\left(\omega C d - \frac{1}{\omega L_0}\right), \quad (2)$$

$$\omega_{c1} = \omega_{c2},\ Z_c = \sqrt{L_0 / C_0}. \quad (3)$$

Here, L_0 and C_0 are found from (2) with the matching condition of (3). The coupled line including two metamaterial units with a C_0 of 1.7 pF and an L_0 of 4.6 nH has a zero phase characteristic at the frequency of 2.45 GHz. The characteristic impedance of 50 Ω and the electrical length of $\pi/4$ are used for calculation. The width of the transmission lines and the spacing between two coupled lines are designed to be 50 μm and 6 μm, respectively.

To achieve a further coupling increase, the metamaterial-based on-chip transmission line is modified to be like a transformer, as shown in Fig. 3(b), symmetrically inter-winding the through line and the coupled line. When the coupler incorporates the configuration of the transformer and metamaterial, the coupling increases by 2.5 dB and 4.5 dB, respectively, as shown in Fig. 4. The simulations represented in Fig. 4 show the directivity of three configurations within 9±1 dB. When a transformer or metamaterial is incorporated to enhance coupling, the magnitude of S_{31} and S_{41} changes by almost the same amount in dB. Therefore, the directivity finally becomes similar.

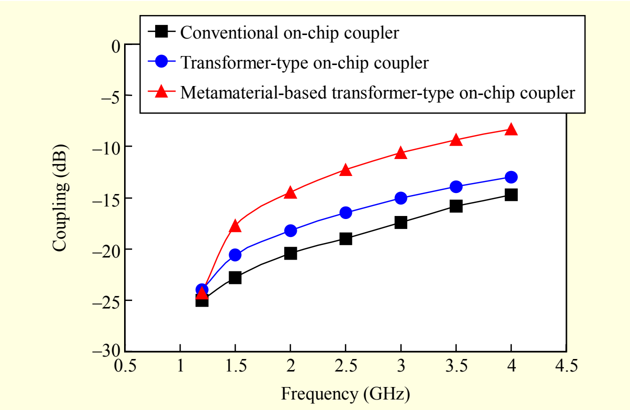

Fig. 4. Coupling simulation results of three different on-chip couplers.

III. Measurements

Figure 5 shows a photograph of the implemented chip. The overall chip size of the PA module, including both the PA and the power detector, is 1,600 μm × 1,700 μm. The PA is

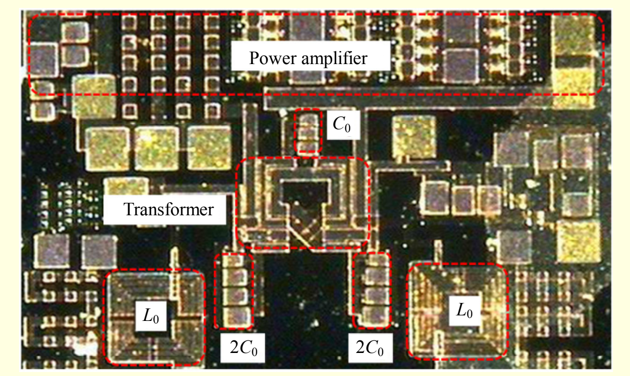

Fig. 5. Chip photograph of power detector using metamaterial-based transformer-type on-chip coupler of PA.

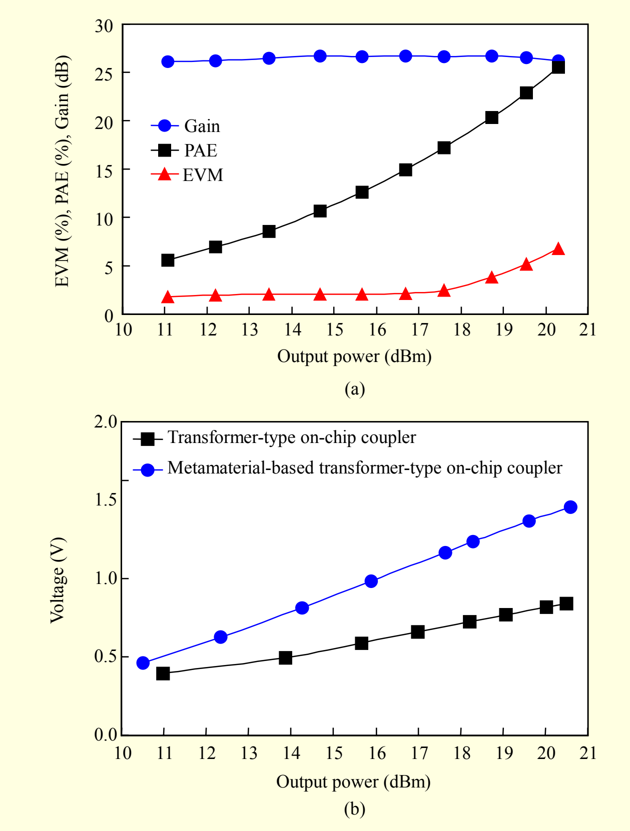

Fig. 6. Measurements of (a) PA performance and (b) power detector performance.

Table 1. Comparison with other on-chip power detectors.

	[1]	[2]	[3]	This work
Technology	SiGe	SiGe	PHEMT	InGaP
Frequency (GHz)	2.4	2	2.6	2.45
Application	WLAN	TD-SCDMA	WiMAX	WLAN
Configuration	Active	Passive	Passive	Passive
Output voltage (V) @ 15-dBm output	1	0.7	0.3	0.9
Voltage slope* (V/dB)	0.04	0.03	0.02	0.1

* Voltage slope is calculated from three points of output power: 10 dBm, 15 dBm, and 20 dBm.

measured with an orthogonal frequency division multiplexed Wi-Fi modulation signal of 64 quadrature amplitude modulation at a frequency of 2.45 GHz, which is the center frequency of the 2.4-GHz wireless local area network (WLAN) application. Because the bandwidth is less than 100 MHz, the measurements show very similar performance at the ends of the band, for example, 2.4 GHz and 2.5 GHz. As shown in Fig. 6(a), an error vector magnitude (EVM) of 3%, power-added efficiency (PAE) of 20%, and gain of 26 dB are achieved at the output of 18 dBm. Figure 6(b) shows the performance of the power detector using two on-chip couplers integrated with the series inductor for output matching. One power detector is configured with only a transformer-type on-chip coupler, and the other is configured with both a transformer and metamaterial. At an output power of 20 dBm, the former has an output voltage of 0.7 V, and the latter has an output voltage of 1.5 V. A comparison between this work and the results published in the literature is shown in Table 1. The slope of the power detector's output voltage in this work is 2.5 times larger than that of the active detector in [1] and 3.3 to 5 times larger than those of the passive detectors in [2], [3].

IV. Conclusion

A power amplifier with an on-chip power detector for 2.4-GHz WLAN application was presented. The power detector includes an on-chip coupled line directional coupler, which was co-designed with an output matching network. The coupler employs a transformer and metamaterial configuration to increase coupling.

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