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Experimental study of integrated tunable transformer

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Abstract: A new tunable integrated transformer topology together with its tuning method is presented. The proposed tunable topology consists of a conventional tapped transformer and a coupled inductor. The phase shift between the input power into the primary winding and that into the coupled inductor was used to control the electrical characteristics such as maximum stable gain, input impedance and quality factor. The new tunable transformer achieved about 3 dB higher maximum stable gain and 2.8 times higher quality factor compared to the conventional transformer.

Keywords: tunable transformer, tunable inductor, integrated trasformer, low voltage circuit design

Classification: Integrated circuits

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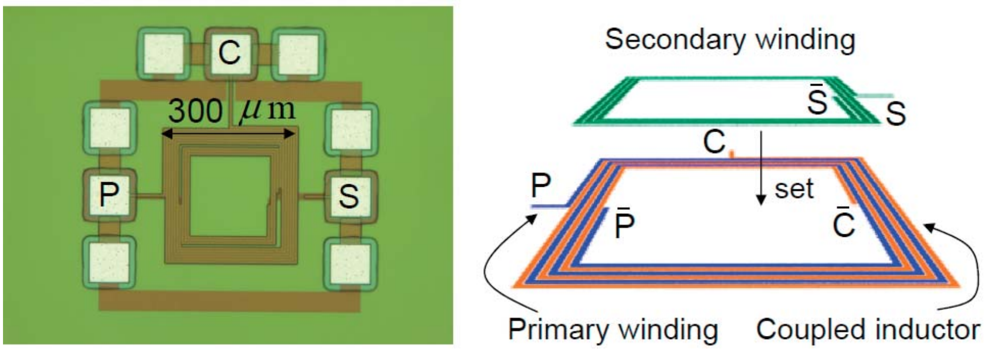
1 Introduction

Low voltage operation and die area reduction have become important issues in the design of radio frequency integrated circuits (RF ICs) for personal communication systems [1]. Monolithic transformers have useful performance characteristics to meet the requirements compared to conventional LC topologies. The inductive or capacitive coupling properties enable low voltage and area efficient designs [1, 2]. Moreover, the transformer winding configuration improves the quality factor of each spiral winding compared to separated inductor topology [3]. A frequency tuning method with varactors is, however, widely employed in transformer-based circuits [1, 4], although advanced tuning techniques with magnetically coupled inductors have been reported [5, 6].

This paper presents a tunable transformer topology in conjunction with its tuning technique based on the concept of magnetically tunable inductor [5]. The maximum stable gain G_{MSG} [7] and input impedance Z_{in} of a conventional transformer, and the quality factor of the primary winding Q_{P} are tuned. The experimental results of tunable and conventional transformers demonstrate that the proposed topology is useful to tune the electrical characteristics of RF transformers in integrated circuits.

2 Tunable transformer and test setup

Figure 1 shows a die microphotograph of the proposed 3-port tunable transformer and the exploded view. A simple tunable spiral inductor structure [5]



(a) (b)

Fig. 1. (a) Die microphotograph of the tunable transformer. (b) Exploded view of the tunable structure.

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was extended to the tunable transformer topology. A spiral microstrip line of the tunable inductor is utilized as the primary winding of the tunable transformer, while the other spiral is used as the coupled inductor. A single inductor brought into the interleaved structure acts as the secondary. The primary and the secondary windings compose a conventional 2-port tapped transformer. The terminals $\bar{\mathrm{P}}$, $\bar{\mathrm{S}}$ and $\bar{\mathrm{C}}$ are grounded. Note that the secondary winding of the proposed transformer is not used in the tunable inductor topology. The test chip was fabricated in a 0.18-μm standard CMOS process. The size of the tunable transformer is 306 μm × 300 μm.

The concept of the tunable transformer is based on the magnetic field change across the tapped transformer. The magnetic flux crossing the transformer is increased or decreased by the induced magnetic field of the coupled inductor. The phase shift in power between the transformer and the coupled inductor is employed to perform the concept. The G_{MSG}, Z_{in} and the Q_{P} of the transformer are tuned by varying the relative phase of power flowing through the transformer and the coupled inductor. Note that G_{MSG}, a figure of merit for a potentially unstable component [7], is a useful measure to characterize the tunable transformer performance rather than maximum available gain used for passive RF elements [8].

Figure 2 shows a test setup to measure the characteristics of the tunable transformer. The port 1 of the vector network analyzer (Agilent Technologies 8722ES) was connected to the primary winding through a directional coupler and to the coupled inductor through a −10 dB directional coupler output, RF power amplifier, fixed attenuators, and a variable phase shifter. The port 2 was directly connected to the secondary winding. The phase shifter was used to control the relative phase between power into the primary winding and that into the coupled inductor. The attenuators were adjusted to obtain a −5 dB total power gain of the shunted drive circuit including the coupler

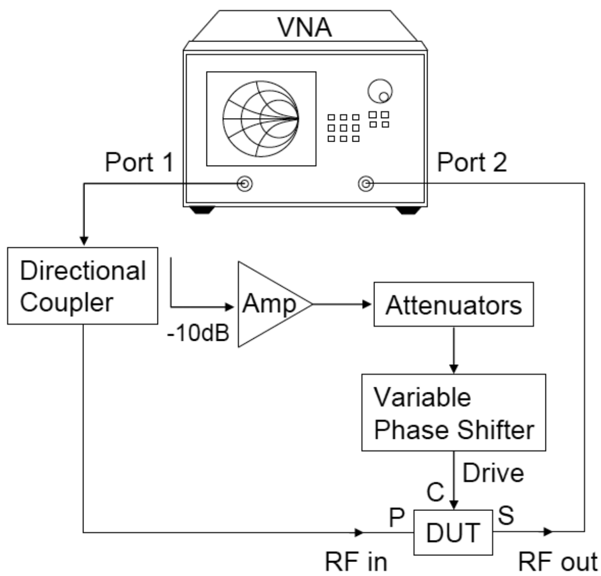

Fig. 2. Test setup for the on-chip tunable transformer (DUT).

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output.

3 Experimental results and discussion

Figure 3 (a) shows the G_{MSG} and the Q_{p} of the tunable transformer tuned by using the phase shifter. The measured results are compared with those of the conventional transformer. Note that the values of the conventional transformer were measured by using the tunable topology with drive port open-circuited. The G_{MSG} on the left axis is defined by

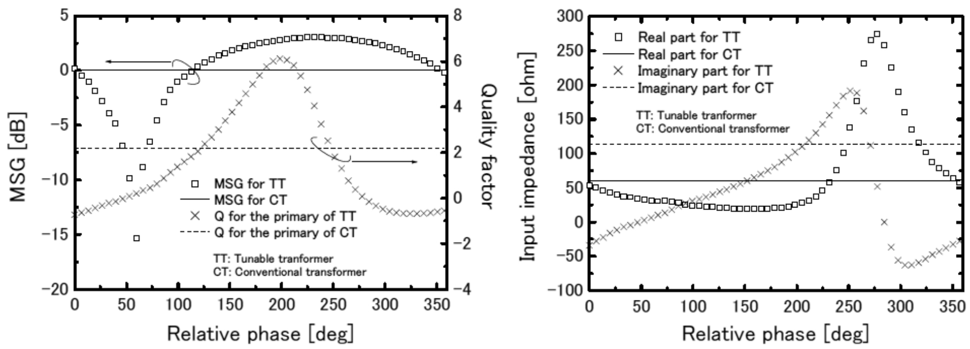
$$G_{\mathrm{MSG}} = \frac{|S_{21}|}{|S_{12}|} \tag{1}$$

where S_{21} and S_{12} are the forward and reverse transmission coefficients, respectively. The quality factor of the primary on the right axis is given by [8]

$$Q_{\mathrm{p}} = \frac{\mathrm{Im}[z_{11}]}{\mathrm{Re}[z_{11}]} \tag{2}$$

where z_{11} is the input impedance at port 1. The plots show that the maximum G_{MSG} of the tunable transformer is about 3 dB higher than that of the conventional structure regardless of the −5 dB power gain of the shunted drive circuit. Moreover, the maximum Q_{p} of the tuned transformer is 2.8 times higher than the Q_{p} of the conventional transformer. The phase shift achieving maximum Q_{p} is near that achieving the maximum G_{MSG} for the tunable transformer. This results indicate that maximizing the Q_{p} leads to a higher G_{MSG}, which agreed with the simple analysis of maximum available gain discussed in [8]. This, however, can be disadvantage of tunable inductors [5, 6] because the power coupled between the inductor and other components [9] can be larger than conventional inductors when the quality factor of the tunable inductors is maximized.

Figre 3 (b) shows Z_{in} of the tunable and the conventional transformers.



(a) (b)

Fig. 3. Measured results of the tunable and the conventional transformers at a 2.76 GHz. (a) Maximum stable gain and quality factor, and (b) input impedance with 50-Ω load resistance are shown.

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The input impedance is given by

$$Z_{\rm in} = z_{11} - \frac{z_{21} z_{12}}{R_{\rm L} + z_{22}} \tag{3}$$

where $R_{\rm L}$ is the 50-Ω load resistance, and z_{11}, z_{21}, z_{12} and z_{22} are the z-parameters of the transformer. The plots indicate a higher $G_{\rm MSG}$ and the maximum $Q_{\rm p}$ (see Fig. 3 (a)) can be achieved by tuning the real part of $Z_{\rm in}$ to the minimum value. The tuning technique can provide impedance matching at a frequency by adjusting the input power to drive the coupled inductor. Note that the measurement results reported in [5] reveal that a variety of power levels changes the real and imaginary parts of the input impedance of a tunable inductor. These results show that the proposed tunable transformer is useful for RF IC designs because of its higher performance compared to the conventional transformer used in RF ICs.

4 Conclusion

The topology, tuning method and the experimental results of on-chip tunable transformer have been reported. The tapped transformer with the coupled inductor was proposed as the tunable structure. The spiral inductor coupled to the tapped transformer was used to tune the maximum stable gain, input impedance, and the quality factor in conjunction with phase shift technique. The measurement results show that about 3 dB maximum stable gain was achieved although the drive power into the coupled inductor was 5 dB less than the power into the primary winding. The measured input impedance indicates that the proposed topology and the tuning method can be used for an impedance matching network. The integration including the external measurement system on a chip is not addressed in this paper, but is the important future work. The tunable transformer concept is an advanced and useful technique for RF IC designs.

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