A 40 GHz, broadband, highly linear amplifier, employing T-coil bandwith extension technique

A 40 GHz, Broadband, Highly Linear Amplifier, Employing T-coil Bandwidth Extension Technique

Hammad M. Cheema[1], Reza Mahmoudi[1], M.A.T. Sanduleanu[2], Arthur van Roermund[1]

[1]Department of Electrical Engineering, Mixed-signal Microelectronics group, Eindhoven University of Technology, 5600 MB, Eindhoven, The Netherlands

[2] Philips Research, Prof. Holstlaan 4, 5656A, Eindhoven, The Netherlands

***Abstract* — This paper presents a broadband, highly linear amplifier suitable for multi-standard mm-wave applications such as car radar, LMDS and satellite return channel. It can also be utilized as an efficient wideband output buffer, for measurements of mm-wave circuit components. It exhibits a 3-dB bandwidth of 40 GHz with a pass-band gain of 6 dB. The presented amplifier is highly linear with an IP3 of +18 dBm. It has been implemented in a bulk 90nm CMOS LP (low power) technology and consumes 3.3 mW from a 1.2 V supply.**

***Index Terms* — CMOS integrated circuits, broadband amplifiers, T-coil, bandwidth enhancement.**

I. Introduction

The increasing demand of high data rate transmissions and multi-standard multi-mode applications sets stringent requirements for RF transceivers and its components. Broadband amplifiers are vital building blocks of such transceivers and can be used for amplification, as well as for matching and measurement purposes.

A broadband amplifier can be an individual building block of an optical transceiver e.g. limiting amplifier, or a part of a building block like the amplification stage of a D-Latch, the gain stage of an oscillator or a multiplexer, etc. The fundamental difference between a broadband amplifier and a tuned or a narrow-band amplifier [1] lies in the difficulty to get high gain and large bandwidths at the same time. This is because the gain-bandwidth product is a technology constant depending on the process node used.

In order to circumvent this limitation, one possible approach is to distribute gain on many stages [2]. Although the process limits the gain-bandwidth product of one stage, gain distribution boosts the total gain-bandwidth product of the complete amplifier. For a second order roll-off in the amplifier, the bandwidth of the total amplifier is:

$$BW_{TOTAL} = BW_{STAGE} * \sqrt[4]{2^{1/n} - 1} \qquad (1)$$

where BW_{STAGE} is the bandwidth of the individual amplifier and n is the number of stages [3]. The price paid in this approach is usually related to higher on-chip real-estate needed and higher power consumption. The main requirement here is to reduce the group-delay distortion of the gain stages by ensuring that peaking at high frequency of the linear blocks is limited.

Other techniques include shunt peaking and f_T doublers [4] but they are less effective in enhancing the bandwidth of the design. The theoretical bandwidth improvement of the shunt-peaking approach is 70%. However, in practice, the bandwidth extension achievable is only 20÷30% [6]. In f_T doublers, the input capacitance is reduced by almost a factor 2, enhancing therefore the input bandwidth of the design. Nevertheless, the output bandwidth is reduced by connecting two devices in parallel at the output. Therefore this approach has also limited value in practice, at millimeter wave frequencies.

The design goal for broadband amplifiers is to maximize gain and bandwidth, and, for an acceptable linearity performance, to minimize power consumption. This paper concerns the theoretical approach, the design and the measurement results of a 40GHz broadband amplifier in a baseline CMOS090 LP process. For bandwidth extension, the T-coil technique is employed. Although known from low frequency designs, by taking advantage of the small dimensions of passive components at mm-waves, this design has a bandwidth extension of more than 100% [5].

The paper is organized as follows. Section II presents the bandwidth extension techniques. T-coil design and implementation is discussed in Section III. Section IV introduces some layout aspects and measurement results of the T-coil amplifier are presented in Section V.

II. Bandwidth Extension Techniques

As mentioned before, inductive peaking and distributed amplification are commonly used techniques for bandwidth extension. It is known that gain of a capacitively loaded amplifier rolls off as frequency increases because the capacitor's impedance diminishes. The introduction of an inductor in series with the load capacitor generates an impedance which increases with frequency (i.e. it introduces a zero). This nullifies the decrease in impedance of the capacitor and results in a constant impedance level over a broader frequency range as compared to the original RC network [6].

Inductive peaking can be achieved in a number of ways, depending on the placement of the coil. The first type is shunt peaking in which the inductance appears in a branch that is parallel with the load capacitance (Fig. 1). The second type is a series peaking system in which the inductance is placed in series with the load capacitance. A combination of shunt and series peaking is also possible and offers increased bandwidth, than can be achieved by each system alone [6].

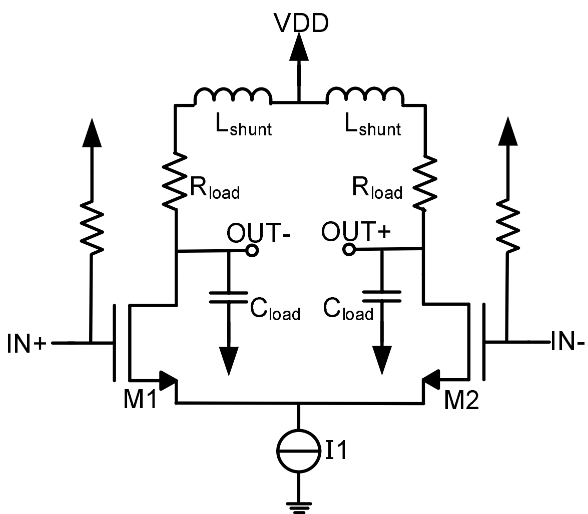

Fig. 1. Shunt peaking differential amplifier

However, the best bandwidth extension method is based on a combination of shunt and double series peaking and is called the T-coil peaking circuit. The circuit schematic of such a network is shown in Fig. 2. The main characteristic of this circuit are the mutually coupled inductors (also referred as transformer) which form a letter 'T' if the mutual inductance is represented by a separate coil, hence the name T-coil is widely used.

The coupling factor k between both halves of the coil (L1a,L1b or L2a,L2b) and the bridging capacitance Cb has a certain relationship, depending on the layout of network poles. For a general RLC circuit, to obtain constant input impedance at any frequency the relation $R = \sqrt{L/C}$ must hold. However, this is true, only in a lossless circuit. In practice, owing to losses, the impedance is only constant up to a certain frequency, which, with careful design, can be high enough to work as a broadband amplifier.

The relation between different components of the T-coil amplifier are shown below according to [5]. ζ is the damping factor and is chosen as $1/\sqrt{2}$ for maximally flat response in the pass-band (also called Butterworth response). L_M is the mutual inductance resulting from the coupling between the two halves of the coil L_{1a} and L_{1b}. Cb, called the bridging capacitance is used to create parallel resonance and provides further bandwidth improvement. C_{load} consists of the output capacitance of the transistors as well as the bond-pad capacitance. Theoretically, the T-coil peaking circuit improves the bandwidth by a factor of 2.83 as compared to a differential amplifier without inductive peaking.

$$L_{1a} = L_{1b} = \frac{R_{load}^{\ 2} C_{load}}{2} \tag{1}$$

$$w_n = \frac{1}{R_{load}\sqrt{Cb\ C_{load}}} \tag{2}$$

$$\zeta = \frac{1}{4}\sqrt{\frac{C_{load}}{Cb}} \tag{3}$$

$$Cb = \frac{C_{load}}{16\zeta^2} = \frac{C_{load}}{4}\left(\frac{1-|k|}{1+|k|}\right) \tag{4}$$

$$L_M = \frac{R_{load}^{\ 2} C_{load}}{4}\left(\frac{1}{4\zeta^2} - 1\right) \tag{5}$$

III. T-Coil Design And Implementation

The T-coil was implemented as an octagonal transformer with an outer ring containing a smaller inner ring as shown in Fig.3. The setup was simulated in Momentum to determine the inductance and coupling coefficient. The portion of the coil from point 'A' to point 'B' forms L_{1a} whereas from point 'B' to 'C' form L_{1b}. The two rings are perfectly symmetric from all sides implying an equal mutual inductance on both sides of the inner ring. The distance between the outer and inner ring is determined for a specific coupling factor. Metal 6 was used for the coil, however, a small portion of Metal 5 was utilized at the cross-over point. Metal 1 was used as fish bone structure under the coil for substrate isolation.

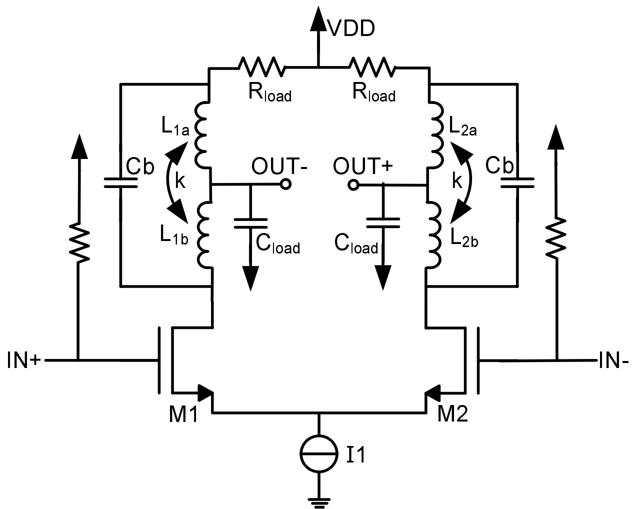

Fig. 2. T-coil peaking differential amplifier

The inductance L_{1a} and L_{1b} have a value of 150 pH and a quality factor of 14 at 40 GHz. The best performance of the amplifier is seen for a coupling factor of 0.3 which corresponds to a mutual inductance of 45 pH. The bridging capacitance of 5fF is implemented as a customized metal-to-metal capacitance. The load resistance is poly-silicon based, with a value of 130 Ω.

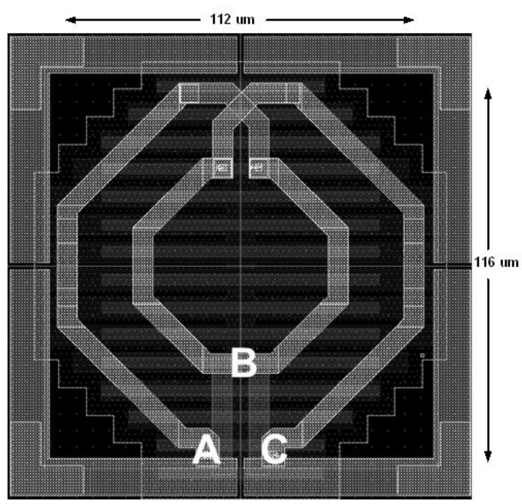

Fig. 3. T-coil implementation

IV. Layout And Technology

The amplifier was fabricated in a bulk CMOS 90nm LP technology suitable for low power applications and offers six metallization layers. The transistors in this technology have a measured f_T and f_{max} of 107 GHz and 280 GHz respectively. The chip micrograph is shown in Fig. 4. The active area of the amplifier is 150 x 300 µm.

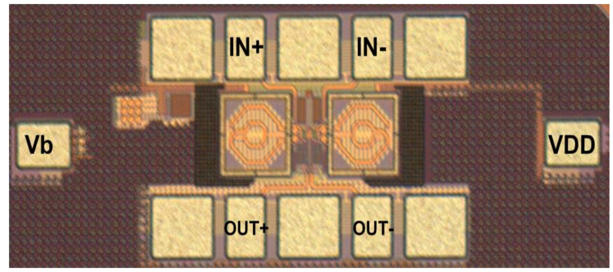

Fig. 4. Chip micrograph of the broadband amplifier

IV. Measurement Results

The broadband amplifier was measured by wafer-probing using high frequency differential probes (GSGSG) and 180° hybrids. Agilent E8361A PNA vector network analyzer and E4448A PSA spectrum analyzer were used for small-signal and large-signal measurements, respectively. Calibration was performed using Short-Open-Load-Thru (SOLT) standard provided by Cascade Microtech's impedance standard substrate (ISS).

The measured small-signal gain (S21) and reverse isolation (S12) of the amplifier are shown in Fig.5. The -3dB bandwidth of the amplifier is 40 GHz and the maximum gain is 6 dB. It is relatively flat over the complete pass-band. The reverse isolation of the amplifier is better than -21.5 dB.

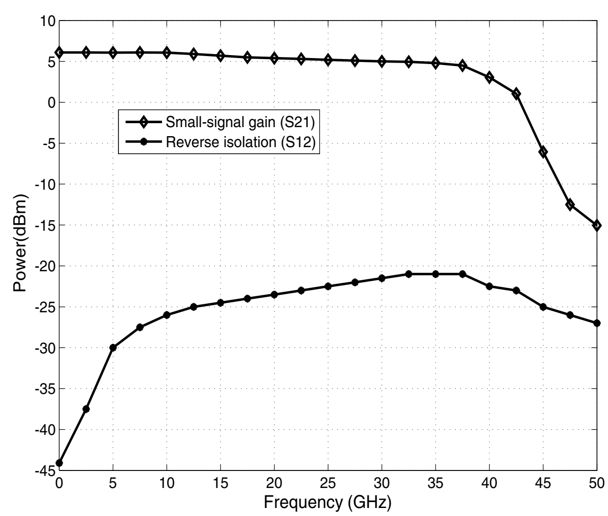

Fig. 5. Gain and reverse isolation of the amplifier

The linearity (IP3 and IP2) of the amplifier is characterized by carrying out two tone tests. Two sinusoidal tones located at 25 and 26 GHz are applied to the amplifier resulting in an IM3 product at 27(and 24) GHz. The spectrum of the output is shown in Fig.6. The input power of the tones is -10 dBm, resulting in an IP3 of +18 dBm.

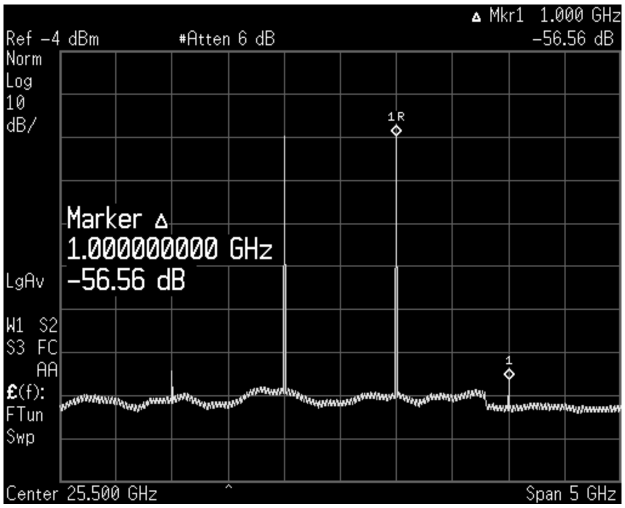

Fig. 6. Spectrum for IP3 two tone test

IP2 was measured by injecting two tones at 25 and 1 GHz, generating IM2 products at 26 (and 24) GHz. The resulting spectrum is depicted in Fig. 7. With an input power of -10 dBm, IP2 is calculated to be +22 dBm. The 1-dB compression point for the amplifier is -4 dBm and it consumes 2.75mA from a 1.2V supply.

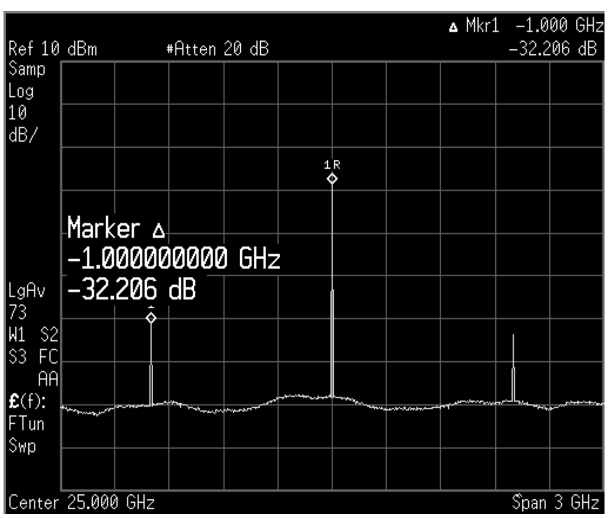

Fig. 7. Spectrum for IP2 two tone test

V. Conclusions

We have presented a broadband amplifier with a 3-dB bandwidth and a pass-band gain of 40 GHz and 6 dB, respectively. This amplifier can be used for multi-standard applications operating in the mm-wave frequency range. It can also be employed as a broadband output buffer for high frequency circuit measurements. The amplifier shows excellent linearity performance with an IP3 of +18 dBm and IP2 of +22 dBm.

Acknowledgement

The authors would like to thank Henry van der Zanden for layout assistance and Philips Research Eindhoven for chip fabrication.

References

[1] Y. Jin et al., “A Millimeter-Wave Power Amplifier with 25dB Power Gain and +8dBm Saturated Output Power”, *Proceedings of European Solid-State Circuits Conference* – ESSCIRC’07, Sept.2007.

[2] S.Galal, B. Razavi, “10Gb/s Limiting Amplifier and Laser/Modulator Driver in 0.18μm CMOS Technology”, *ISSCC Dig. Of Tech. Papers,* pp.188-189, Feb. 2003.

[3] M.A.T. Sanduleanu, “Inductor-less, 10Gb/s limiter with 10mV sensitivity and offset/temperature compensation in baseline CMOS18”, *Proceedings of European Solid-State Circuits Conference* – ESSCIRC’03, Sept. 2003.

[4] Hammad M.Cheema et al., “A Ka Band, Static, MCML Frequency Divider, in Standard 90nm-CMOS LP for 60 GHz Applications,” RFIC Symposium, pp. 541-544, June 2007.

[5] Peter Stari , Erik Margan, “Wideband Amplifiers,” *Published by Springer*, 2006.

[6] Thomas H. Lee, “Planar Microwave Engineering,” *Published by Cambridge*, 2004.