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Millimeter Wave I/Q Generation with the Inductive Resonator Matched Poly-Phase Filter

Ki-Jin Kim, Sanghoon Park, and K. H. Ahn

Abstract**—**A way of generating millimeter wave I/Q signal using inductive resonator matched poly-phase filter is suggested. Normally the poly-phase filter generates quite accurate I/Q phase and magnitude but the loss of the filter is considerable due to series connection of passive RC components. This loss term directly increases system noise figure when the poly-phase filter is used in RF Front-end. The proposed matching method eliminates above mentioned loss and in addition provides gain on the passive filter. The working algorithm is illustrated by mathematical analysis. The generated I/Q signal is used in implementing millimeter wave phase shifter for the 60 GHz communication system to verify its effectiveness. The circuit is fabricated in 90 nm TSMC RF CMOS process under 1.2 V supply voltage. The measurement results showed that the suggested method improved gain by 6.5 dB and noise by 2.3 dB. The summary of the proposed I/Q generation is compared with previous works.

Keywords**—**Millimeter Wave Circuits, Local Distribution, I/Q Generator.

I. INTRODUCTION

RECENTLY 60 GHz high speed short range wireless communication for WPAN(Wireless Personal Area Network) and wireless HD(High Definition) streaming has been released. This new market requires low cost 60 GHz transceiver that has almost 10m communication range which is hard to achieve especially when silicon process is adopted. Fortunately phased-array transceiver architecture showing a controllability of radiation beam pattern, supplies the required effective isotropic radiation power and spatial coverage even in mm-wave CMOS area [1].

The key component of the phased-array system is the phase shifter that provides low and equal insertion loss and accurate phase controllability over the whole operating frequency. There are various types of phase shifter: switched delay[2], loaded line[3], and I/Q modulator[1,4]. Considering low and equal insertion loss and accurate phase shifting across the required band, the I/Q modulator based structure is chosen as a prototype.

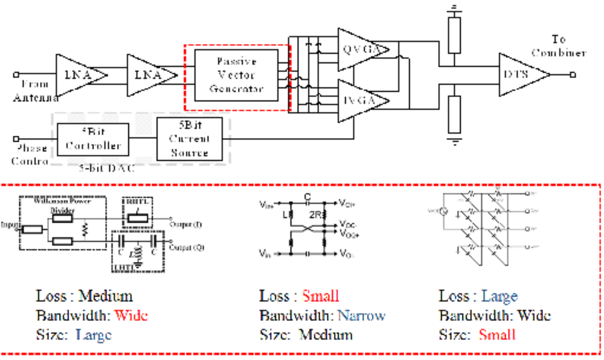

Fig. 1 General block diagram of phase shifter and three applicable I/Q generators

The I/Q modulator based phase shifter requires 60 GHz I/Q generator with low noise, small size, and wide bandwidth. The three different I/Q generation methods are compared in Figure 1. First method is Wilkinson divider based I/Q generator. It shows wide bandwidth with reasonable loss but it consumes the largest chip area among all. Second method, QAF (Qaudrature All-pass Filter) shows small insertion loss with reasonable size but its bandwidth is too narrow to cover the whole 60 GHz band. The third method, poly-phase filter has a strongpoint in size and bandwidth. However, the loss introduced by poly-phase filter is the largest of the three and therefore it is not frequently used in receiver signal path.

In this paper, inductive resonator matched poly-phase filter is suggested to eliminate the insertion loss of the filter and even to provide gain on the system. The paper consists as follows: Section II derives mathematical effects of the inductive resonator matching on poly-phase filter. Section III illustrates the structure of the phase shifter circuit and its operational characteristics. Section IV proves effectiveness of the proposed method by measuring designed circuit.

II. MATHEMATICAL ANALYSIS OF INDUCTIVE RESONATOR MATCHING

Figure 2 shows structure of the proposed inductive resonator matching poly-phase filter. The C_p is sum of the parasitic capacitances of next stage gate oxide and interconnection metal. The TL1~4 = TL are works as a matching inductor L_p. The KCL equations of each node are described as follows:

Ki-Jin Kim is with the Korea Electronics & Technology Institute,#68 Yatapdong Bundang gu Gyoenggi do, Korea (phone: 82-31-789-7226; fax: 82-31-789-7259; e-mail: sergeant@ keti.re.kr).

Sanghoon Park is with the Korea Electronics & Technology Institute,#68 Yatapdong Bundang gu Gyoenggi do, Korea (phone: 82-31-789-7239; fax: 82-31-789-7259; e-mail: parksh@ keti.re.kr).

K. H. Ahn is with the Korea Electronics & Technology Institute,#68 Yatapdong Bundang gu Gyoenggi do, Korea (phone: 82-31-789-7225; fax: 82-31-789-7259; e-mail: khajoh@ keti.re.kr).

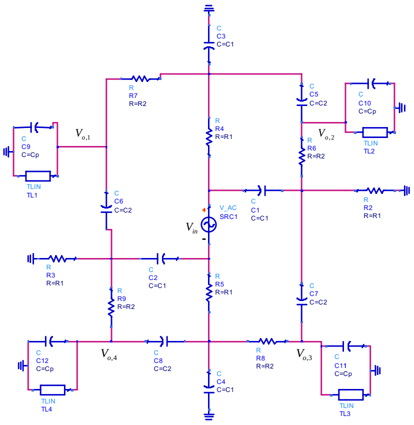

Fig. 2 Proposed inductive resonator matching I/Q poly-phase filter

$$\left\langle \begin{array}{l} \left[1+jR_2\left(Y_2+Y_L\right)\right]\left[\left(R_1+R_2\right)+jR_1R_2\left(Y_1+Y_2\right)\right] \\ -R_1+R_1R_2R_2Y_2Y_2 \end{array} \right\rangle V_{o,1}-jR_1R_2Y_2V_{o,2}-jR_2Y_2R_1V_{o,4} \tag{1}$$
$$=R_2V_+-R_2Y_2R_2R_1Y_1V_-$$

$$\left\langle \begin{array}{l} \left[1+jR_2\left(Y_2+Y_L\right)\right]\left[\left(R_1+R_2\right)+jR_1R_2\left(Y_1+Y_2\right)\right] \\ -R_1+R_1R_2R_2Y_2Y_2 \end{array} \right\rangle V_{o,2}-jR_1R_2Y_2V_{o,3}-jR_2Y_2R_1V_{o,1} \tag{2}$$
$$=jR_2R_1Y_1V_++jR_2Y_2R$$

$$\left\langle \begin{array}{l} \left[1+jR_2\left(Y_2+Y_L\right)\right]\left[\left(R_1+R_2\right)+jR_1R_2\left(Y_1+Y_2\right)\right] \\ -R_1+R_1R_2R_2Y_2Y_2 \end{array} \right\rangle V_{o,3}-jR_1R_2Y_2V_{o,4}-jR_2Y_2R_1V_{o,2} \tag{3}$$
$$=R_2V_--R_2Y_2R_2R_1Y_1V_+$$

$$\left\langle \begin{array}{l} \left[1+jR_2\left(Y_2+Y_L\right)\right]\left[\left(R_1+R_2\right)+jR_1R_2\left(Y_1+Y_2\right)\right] \\ -R_1+R_1R_2R_2Y_2Y_2 \end{array} \right\rangle V_{o,4}-jR_1R_2Y_2V_{o,1}-jR_2Y_2R_1V_{o,3} \tag{4}$$
$$=jR_2R_1Y_1V_-+jR_2Y_2R_2V_-$$

The relation between above equations and I/Q output are $I_{out}(\omega) = V_{0,1} - V_{0,3}$ and $Q_{out}(\omega) = V_{0,2} - V_{0,4}$

$$\left\langle \begin{array}{l} 1-R_1R_2Y_1Y_2-R_1R_2\left(Y_1+Y_2\right)Y_L \\ +j\left[R_1\left(Y_1+Y_2\right)+\left(R_1+R_2\right)\left(Y_2+Y_L\right)\right] \end{array} \right\rangle I_{out}(\omega)=\left(1+R_1R_2Y_1Y_2\right)V_{in}(\omega) \tag{5}$$

$$\left\langle \begin{array}{l} 1-R_1R_2Y_1Y_2-R_1R_2\left(Y_1+Y_2\right)Y_L \\ +j\left[R_1\left(Y_1+Y_2\right)+\left(R_1+R_2\right)\left(Y_2+Y_L\right)\right] \end{array} \right\rangle Q_{out}(\omega)=j\left(R_1Y_1+R_2Y_2\right)V_{in}(\omega) \tag{6}$$

Therefore the transfer function H (jω) is described as follows:

$$H(j\omega)=H_1(j\omega)+jH_2(j\omega) \tag{7}$$
$$=\frac{V_{out}(j\omega)}{V_{in}(j\omega)}=\frac{\left(1+R_1R_2Y_1Y_2\right)+jj\left(R_1Y_1+R_2Y_2\right)}{D(j\omega)}$$

$$D(j\omega)=1-\omega^2R_1R_2\left[C_1C_2+\left(C_1+C_2\right)\left(C_p-\frac{1}{\omega^2L_p}\right)\right] \tag{8}$$
$$+j\omega\left[\left(R_1C_1+2R_1C_2+R_2C_2\right)+\left(R_1+R_2\right)\left(C_p-\frac{1}{\omega^2L_p}\right)\right]$$

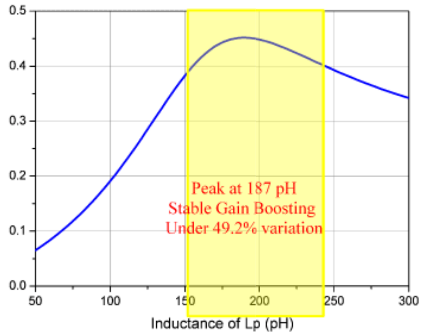

Fig. 3 Magnitude of the each output voltage of the poly-phase filter versus L_p

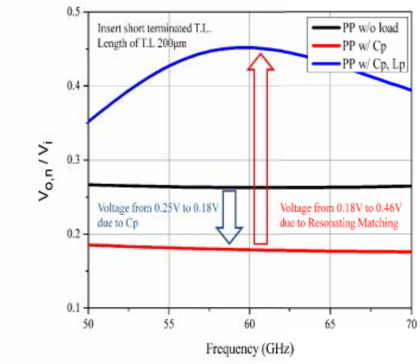

Fig. 4 Comparison of three differential poly-phase filter cases with different matching condition

The I/Q output of the proposed circuit is equated as below:

$$I_{out}(\omega)=\frac{1+\omega^2R_1R_2C_1C_2}{D(j\omega)}V_{in}(j\omega) \tag{9}$$

$$Q_{out}(\omega)=\frac{j\omega\left(R_1C_1+R_2C_2\right)}{D(j\omega)}V_{in}(j\omega) \tag{10}$$

As one can see the magnitude of the denominator is reduced by resonance combination of C_1, C_2, C_p, and L_p which will provide voltage gain on poly-phase filter. To find out the value of Lp that maximize the voltage transfer function, below differential equation is suggested:

$$\frac{\partial\left|D(j\omega)\right|^2}{\partial L_p}=0\Rightarrow\frac{1}{\omega^2L_p} \tag{11}$$
$$=C_p+\frac{\left(1+\omega^2R_2R_2C_1C_2\right)R_1R_1\left(C_1+C_2\right)+\left(R_1+R_2\right)^2C_2}{\omega^2R_1R_1R_2R_2\left(C_1+C_2\right)^2+\left(R_1+R_2\right)^2}$$

For 60 GHz poly-phase filter, this paper adopts C_1 = 25f, C_2 = 26f, C_p=15f, R_1=86.5 Ω, R_2 = 113.5 Ω respectively. Then the calculated L_p for maximum gain is 187pH which is illustrated in Figure 2. As one can see from the figure, inductance sensitivity to the efficiency of the gain boosting is quiet low so the usefulness of the proposed method in commercial purpose is confirmed. Figure 4 compares voltage transfer function of three differential cases: PP(poly-phase filter) without load, PP with only C_p load, and PP with C_p, L_p load. When applied 1V V_{in}

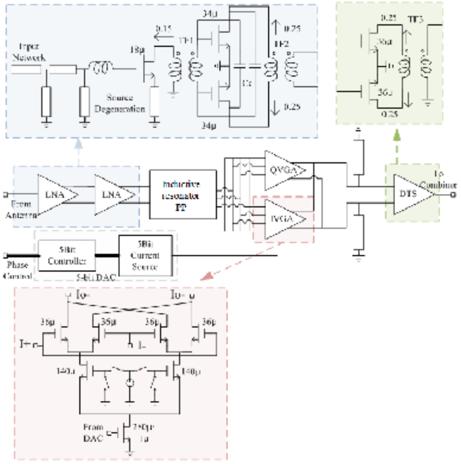

Fig. 5 Proposed Phase shifter circuit adopting inductive resonator

signal, the output of the poly-phase filter is improved from 0.18V to 0.46V by using inductive resonator matching. To implement 187 pH L_p, 200μm TL(Transmission Line) are used in this paper.

III. Proposed Circuit Structure for Verification

The proposed 60 GHz LNA is designed by two cascade Common Source(CS) amplifiers(Fig. 5). CS is used in this paper instead of Cascode because CS shows lower noise figure than Cascode. For the input LNA, simultaneous noise and power matching was achieved by adopting TL source degeneration. The input network consisting of shunt TL (100μm) and series TL (40μm) is designed for matching and ESD protection. All the TL and transformers used in this paper are modeled by full 3D EM simulation.

The TF1 (1:2 ratio) transformer is employed to drive differential input of the inductive resonator matched poly-phase filter and to work as a wide band inter-stage matching component. The primary winding serves as a shunt peaking load for the first CS amplifier and the second winding works as a series inductor for the second stage matching.

In the second stage, TF2(1:1 ratio) transformer load is also used for rejecting common mode signal caused by the first stage CS amplifier. When the load is tuned for ωo= $1/\sqrt{L_L(C_d+C_L)}$, the peak voltage gain of the second CS LNA is represented as:

$$\frac{V_{out}}{V_{in}}(j\omega)=\frac{g_m r_o - j\omega_o r_o C_{gd}}{1+r_o R_s(\omega_o C_{gd})^2 + j\omega_o R_s[C_{gd}+C_{gd}(1+g_m r_o)]} \qquad (12)$$

where Rs, Cd and Cgd are source resistance, effective drain capacitance and overlap capacitance between gate and drain respectively. As shown in (1) the gain is reduced due to the miller capacitor CM(=Cgs(1+gmro)). In the proposed design, the miller compensation capacitor (Cc=Cgd) is inserted between differential gate and drain nodes to eliminate the undesirable feedback capacitor Cgd in the CS amplifier.

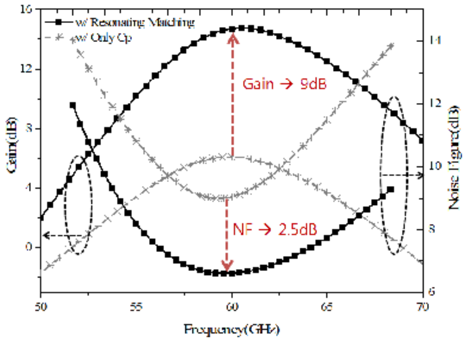

Fig. 6 Comparison of simulated gain and noise figure performances of the phase shifter

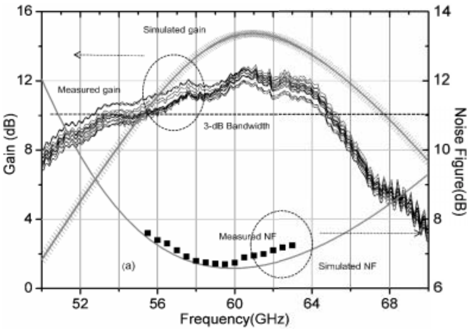

Fig. 7 Comparison of S-parameter results between simulation and measurement

The DTS amplifier is located at the end of the proposed building block and transforms a differential signal into a single signal. This block is necessary for the phase shifter to simply drive the following single ended power combining circuit. It also utilizes TF3(1:1 ratio) transformer for wideband differential-to-single operation.

The I/Q signal is generated by summation of I and Q VGA output which is controlled by digital 5bit DAC. The 5bit output of the DAC manipulates the magnitude and polarity of I /Q VGA.

IV. Simulation and Measurement Results

The gain and noise figure comparison of simulated phase shifter is depicted in Figure 6. As illustrated in previous equation, proposed resonating matching method improves gain and noise response of the poly-phase filter. From the simulation results, a 9 dB gain enhancement and 2.5 dB noise figure improvement are estimated.

To verify resonating matching in real circuit, the proposed phase shifter was fabricated using 90 nm TSMC CMOS process. The chip size, including the pads, is 790μm X 900μm which is quite small comparing to previous studies [5, 6]. The circuit draws 50mA DC current under 1.2V supply. The S-parameter of the designed circuit was measured using RF probes. The simulated and measured S-parameters are compared in Figure 7.

TABLE I
COMPARISON WITH PREVIOUS RESEARCH RESULTS

Ref	7	5	6	8	This work
Structure	PS	LNA + PS	LNA+PS	PS	LNA+PS
Gain	-2	8	12	-4	12.5
NF(dB)	17	6.9	7.2	-	6.4
IP1dB (dBm)	-7	-33.5	-16	-	-13.3
Technology	0.13μm Bi-CMOS	0.12 μm Bi-CMOS	65 mm CMOS	90 mm CMOS	90 mm CMOS
Phase Resolution	Analog	Analog	Digital 22.5^0	Analog	Digital 11.25^0
Chip area(mm^2)	1.48	1.25	0.8	0.504	0.35
Power (mW)	32	66	78	15.6	60

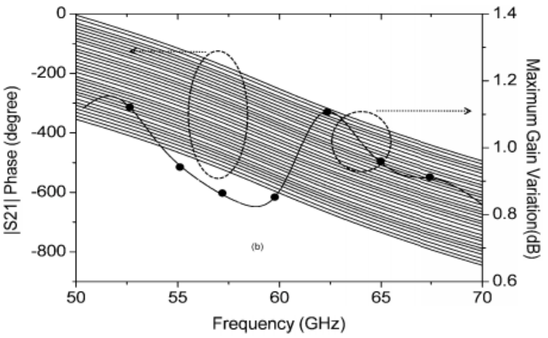

Fig. 8 Measured phase response of the proposed circuit

The results of the S-parameter showed only 2.5 dB gain and 0.2 dB noise figure deviation from results of simulation which is reasonable figure considering 60 GHz frequency, therefore the measurement results verifies the effectiveness of the proposed inductive resonator matching method. The measured results revealed that 6.5 dB gain and 2.3 dB noise figure were improved comparing to S-parameter of the simulation.

The phase accuracy of the proposed method was confirmed by measuring phase response of the phase shifter because accurate phase responses are comes from exact I/Q generation. Figure 8 illustrates measured phase response over the 50 ~ 70 GHz frequency band. The measurement results explained the proposed method produces accurate I/Q generation over the wide bandwidth.

V. CONCLUSION

A way of generating low loss I/Q signal using inductive resonator matched poly-phase filter was presented. By using poly-phase filter as a prototype, wide band I/Q generation was easily achieved with small chip area. Due to the proposed resonator matching, insertion loss by poly-phase filter was totally eliminated. The measurement results showed that the method improves gain by 6.5 dB and noise by 2.3 dB. The Table I summaries this paper with comparing to previous works.

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