Broadband and Highly Accurate X-Band Vector-Sum Phase Shifter Using LC-Type Power Splitter

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***Abstract* — In recent years, for the realization of the low-cost and multi-band APAA (Active Phased Array Antenna) system, broadband and highly accurate vector-sum phase shifter has attracted the attention. To realize such a vector-sum phase shifter, one of the difficulty arises from the trade-off between a bandwidth and an insertion loss of the PPF (Poly Phase Filter) which is deployed at the first stage inside the phase shifter and generates quadrature signals from a differential signal. In order to ease the trade-off of PPF, we propose the PPF using inductor and capacitor (LC-type) power splitter implemented in front of it. Simulation results with the proposed technique show the improvement of 2.7dB in the insertion loss, without degradation of the bandwidth. As a proof of concept, vector-sum phase shifter with the proposed PPF technique was fabricated using 0.18um SiGe BiCMOS process. Measurement results showed the 3dB gain bandwidth of 64% at X-band and the RMS phase error of less than 2.1°. This broadband and highly accurate results show that the proposed PPF technique is effective to realize multi-band APAA system in the near future.**

***Keywords* — phase shifters, poly phase filters, SiGe, CMOS.**

I. Introduction

APAA (Active Phased Array Antenna) has become one of the most attractive technology for applications like data communication and/or radar system applied to consumer, military, aerospace and automotive products. The APAA generates arbitrary beam patterns, using massive number of array antenna elements. And each antenna element needs the highly accurate and low-cost phase and amplitude control component. In order to meet these requirements, vector-sum phase shifters fabricated with silicon process have been reported [1-3].

Another demand for APAA is the multi-purpose operation, which enables the operating mode to be switched arbitrarily, e.g. a data communication, a radar application, an electric warfare and so on [4]. For the multi-purpose operation, extremely broadband APAA is necessary. Hence key blocks like a phase shifter and a variable attenuator must cover all the operating bands. The broadband impedance matching technique is useful to make amplifiers operate in various frequency range. But in the case of phase shifter design, another difficulty arises on how to control the phase and amplitude accurately, regardless of the operating frequency.

In the vector-sum phase shifter, there is a trade-off between noise performance and phase control accuracy. The trade-off comes from the insertion loss of the PPF which is deployed at the first stage inside the phase shifter. In general, more number of stages of PPF leads to worse insertion loss, but wider bandwidth of the quadrature signal generation. In order to overcome this trade-off, a new technique which implements the reactance network in front of vector-sum phase shifter is presented in this paper.

II. Circuit Implementation

A. Basic Operation of Vector-Sum Phase Shifter

Circuit diagram of vector-sum phase shifter and a vector diagram of its operation, are depicted in Fig. 1(a) and Fig. 1(b) respectively. The phase shifter consists of PPF and IQ (In-phase and Quadrature) -VGA (Variable Gain Amplifier). The PPF generates quadrature signals from a differential signal. The IQ-VGA adjusts the amplitudes of incoming in-phase and quadrature differential signals, so that the phase of the summed output signal represents a desired phase and a constant amplitude.

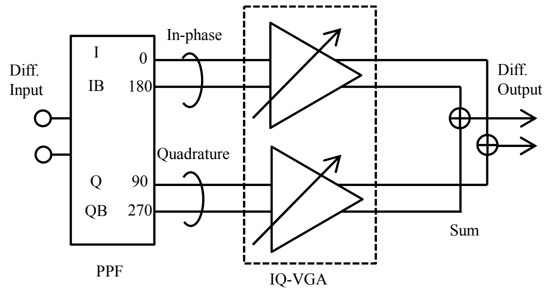


Fig. 1(a). Circuit diagram of vector-sum phase shifter

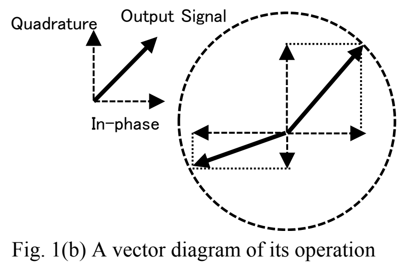


Fig. 1(b) A vector diagram of its operation

B. Implementation of LC-Type Power Splitter in PPF

The PPF is placed at the first stage of a vector-sum phase shifter. It consists of passive components like resistors and capacitors and has a certain amount of insertion loss. A conventional circuit diagram of a 2nd order PPF is shown in Fig.2. In this configuration, the total insertion loss is 9dB including the ideal splitting loss of 3dB. The excess loss of 6dB consists of the resistive loss (3dB) and the additional loss (3dB) as noted in Fig.2.

The resistive loss comes from first stage circuit of the PPF. Because the PPF has two inputs and four outputs, two terminals out of four input terminals are shorted to the others. In this configuration, the signals at input terminals cannot be the quadrature signals. As a result, the excess power consumption across the resister causes the resistive loss of 3dB.

In order to obtain wider bandwidth, it is preferable to use the higher order PPF by increasing the number of cascaded stages without any matching circuit at inter-stage. But this cascaded stages causes the additional loss of 3dB multiplied by the number of additional stage. In the PPF shown in Fig. 2, the additional loss is 3dB.

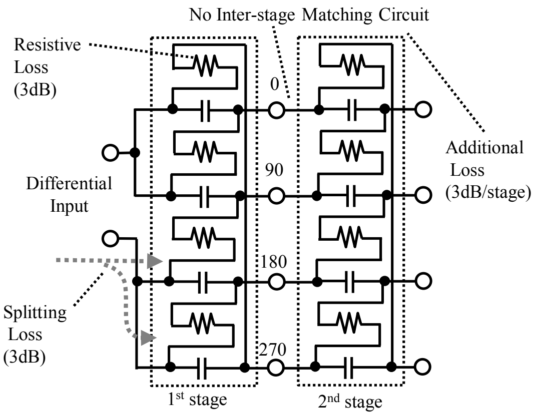


Fig. 2 Circuit diagram of the conventional PPF

A circuit diagram of the proposed PPF is shown in Fig.3. The primary purpose is to reduce the resistive loss. LC-Type power splitter is placed between the differential input and four input terminals of the 1st stage circuit. It consists of the least number of components, i.e. two inductors and two capacitors, so that the chip area can be minimized. It works both as an input matching network and a quasi-quadrature signal generator. Expected improvement of the insertion loss can be up to 3dB. It also improves NF of the phase shifter with same extent.

To maximize the effect of this configuration, it is better to decide the component values so as to prioritize the input matching, and generate a certain amount of phase difference at the four output terminals in the LC-Type power splitter. By generating the quasi-quadrature signals, the resistive loss in the first stage can be minimized, hence it leads to low insertion loss of the PPF.

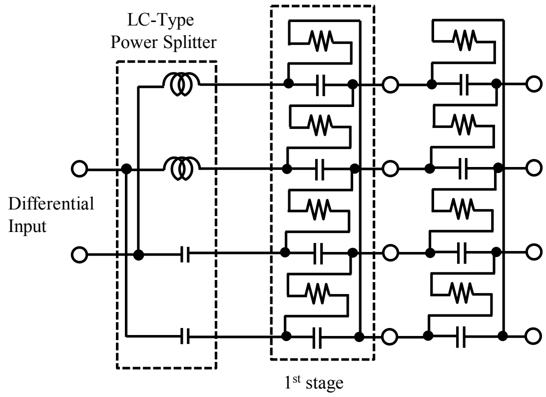
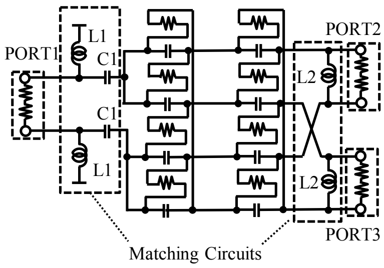


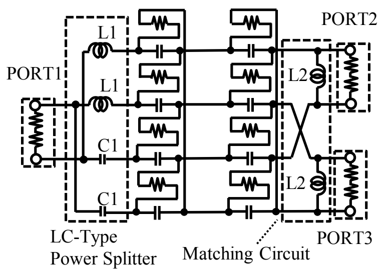
Fig. 3 Circuit diagram of the proposed PPF

In order to show the effectiveness of the proposed configuration, an example of design parameter and simulation results are discussed. The schematics of conventional and proposed PPFs optimized for 10GHz are shown in Fig.4 (a) and (b), respectively. For a fair comparison, the input and output matching networks are also implemented. In this example, the LC-type power splitter generates a phase difference of about 120 degrees not 90 degrees. Even such a rough quadrature signal generator is enough to reduce the resistive loss.



Resistor	50 ohm
C1	2 pF
L1	477 pH
L2	1592 pH
Remaining Cap.	318 fF
Impedance of PORT1,2,3	100 ohm

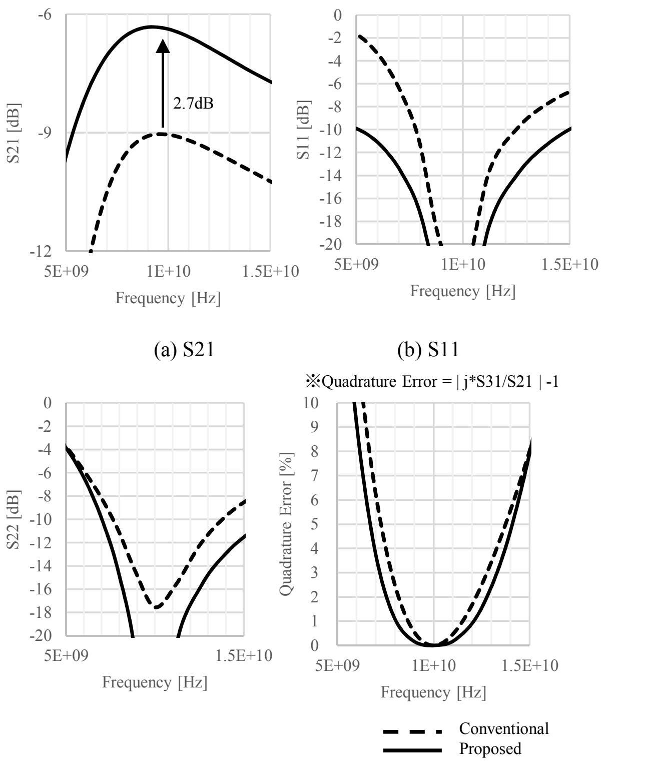
Fig.4 (a) Circuit parameters for conventional PPF



Resistor	50 ohm
C1	796 fF
L1	1123 pH
L2	1592 pH
Remaining Cap.	318 fF
Impedance of PORT1,2,3	100 ohm

Fig.4 (b) Circuit parameters for proposed PPF

Typical simulation results of S21(~S31), S11, S22, and quadrature error are presented in Fig. 5 (a), (b), (c) and (d), respectively, where the dashed-line is for the conventional PPF and the solid line is for the proposed PPF. The improvement of 2.7dB in the insertion loss is obtained. Not only S21 but also S11, S22 and the quadrature error are better in wide frequency range. Especially the improvement of the quadrature error are necessary to realize a broadband and accurate phase shifter.



(a) S21 (b) S11

(c) S22 (d) Quadrature Error

Fig.5 Typical simulation results from the conventional PPF (dashed lines) and the proposed PPF (solid lines)

III. Experiment Results

X-band 6-bit phase shifter with the proposed configuration was designed using 0.18um SiGe BiCMOS Process. For an APAA usage, a variable attenuator of 32dB range with 1dB step was also implemented. The schematic of the phase shifter is depicted in Fig.6. The proposed PPF is adopted as the quadrature generator whose parameter is same as one depicted in Fig.4 (b). To make the circuit compact, I/Q-VGA in the phase shifter and the variable attenuator were implemented in the cascode topology. Therefore both circuits employ the current steering configuration. The detailed schematic of the current steering circuit is shown in Fig.7. The 6-bit digital control and the decoder logic switch on or off for the base current of each differential pair in a unit cell so that the current flowing from the emitter terminals to output terminals is controlled digitally.

A chip photo of the fabricated phase shifter is shown in Fig. 8. The area of the core circuit is 1.6mm x 0.4mm and the measured power consumption is 133mW from 3.3V supply. On-wafer measurement was conducted with GSG probing and the calibration reference plane of GSG PAD. The phase and amplitude of the output signal were controlled through the 3-wire serial to parallel interface arranged at DC probe pins.

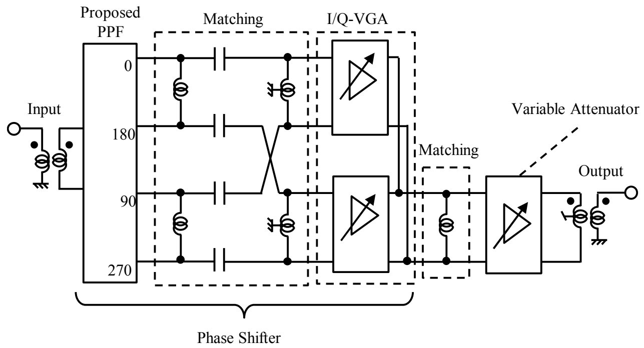


Fig.6. Schematic of phase shifter

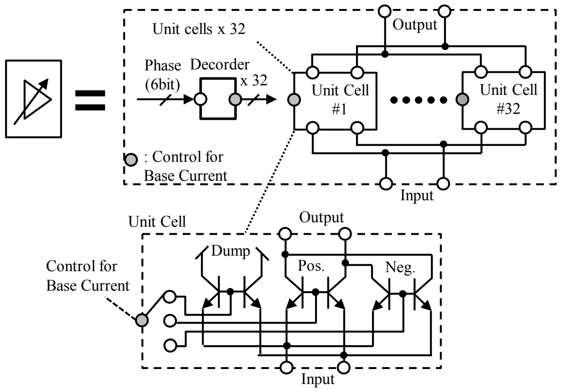


Fig.7 Detailed schematic of current steering circuit

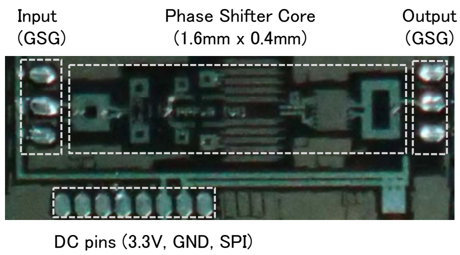
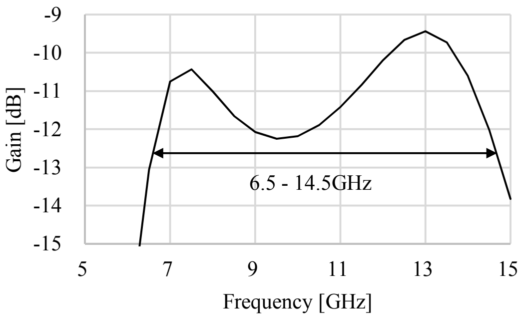
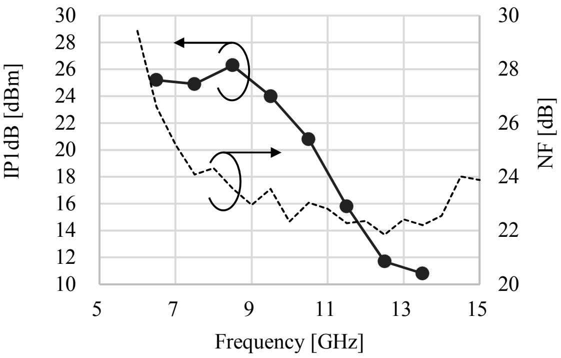


Fig.8 A chip photo of the fabricated phase shifter

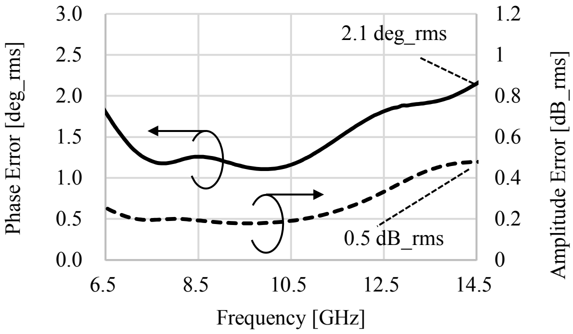
The measurement results of gain, IP1dB (Input 1dB Compression Point) / NF, phase control characteristic and variable attenuator characteristic are shown in Fig.9 (a)-(d), respectively. 3dB bandwidth of the gain was 6.5-14.5GHz, (Relative bandwidth of 67%). The RMS phase error of less than 2.1 ° and the RMS amplitude error of less than 0.5dB without any calibration were achieved. The variable attenuator achieved 31dB gain control range with the RMS amplitude error of less than 0.5dB and the phase variation of less than 14 °.



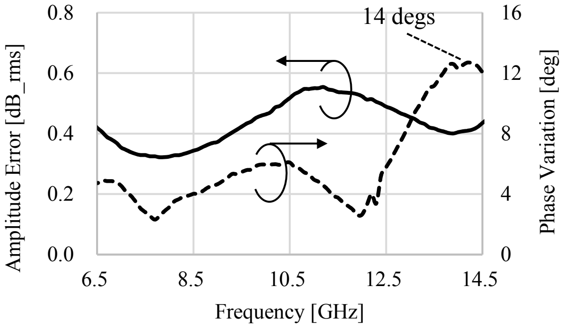
(a) Gain (S21)



(b) Input 1dB compression point and noise figure



(c) Phase shifter characteristic



(d) Variable attenuator characteristic

Fig.9. Measurement results

Table. 1 shows a comparison of State-of-the-Art for reported vector-sum phase shifters [1-3]. The phase shifter implemented with the proposed LC-type power splitter shows the best phase accuracy with the reasonable bandwidth.

Table 1. A comparison of state-of-the-art

	[1]	[2]	[3]	This work
Frequency [GHz]	6 – 18	8 - 12	8 – 12	6.5 – 14.5
Phase Control [bit]	5	6	6	6
Gain [dB]	19.5	-2.5	11.5	-9.5 ~ -12.5
RMS phase error [°]	5.6	6.4	2.2	< 2.1
RMS Amplitude Error [dB]	1.1	2	0.9	< 0.5
Power Consumption [mW]	61	110	195	133
IP1dB [dBm]	-40	-11	-15	+11 ~ +26
NF [dB]	5.7	-	-	14 ~ 27
Technology	0.18um SiGe	0.25um SiGe	0.13um SiGe	0.18um SiGe
Published Year	2010	2016	2017	2018

IV. Conclusions

In this paper we proposed a new PPF implementation technique where the LC-type power splitter is deployed in front of PPF for the vector-sum phase shifter. As a proof of concept, phase shifter with proposed PPF technique was fabricated using 0.18um SiGe BiCMOS process. Measurement results showed the 3dB gain bandwidth of 64% at X-band and the RMS phase error of less than 2.1°. These broadband and highly accurate results show that the proposed PPF configuration is effective to realize multi-band APAA system in the near future.

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