Design and Implementation of Micromachined Lumped Quadrature (90°) Hybrids

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Abstract- **To reduce the chip size of a quadrature hybrid at frequencies below K-band, lumped components have been employed to replace the transmission line segments. Systematic analysis and design technique has been developed. For the first time, X-band lumped quadrature hybrids with low insertion loss and wide bandwidth have been fabricated using a micromachined process technology. Approximately, two order of magnitude area reduction has been achieved by this approach compared with distributed designs.**

I. INTRODUCTION

A quadrature hybrid is a four-port network in which the incident power is divided between two output ports, called the direct and coupled port, while the forth port is isolated from the input port. Furthermore, each port is matched so that the reflection coefficient at each port is zero. Normally, this type of hybrid consists of four transmission line segments and is also known as branch-line hybrid. It is an indispensable component for applications such as microwave phase shifts, power amplifiers and balanced-structure circuits.

Since the dimension of the quadrature hybrid is proportional to the wavelength of the operating frequency, its size becomes prohibitively large for MMIC applications at frequencies below K-band. For example, a 8.5 GHz branch-line coupler on Si substrate will have dimensions approximately 16 mm^2. To solve this problem, 90° hybrids have been demonstrated with lumped elements [1]-[3] in place of the transmission lines. In this paper, a systematic analysis and design technique is presented for lumped element hybrid coupler design. Then, 8.5 GHz lumped element hybrid couplers comprised of micromachined passive components [4] that have a high quality factor and resonant frequency are fabricated and characterized for the first time. The measured characteristics of these circuits demonstrate low insertion loss and wide bandwidth while greatly reducing circuit size.

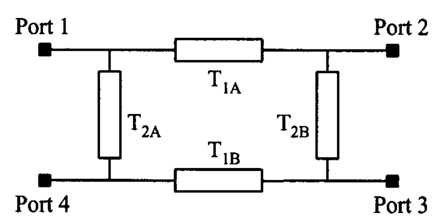
II. ANALYSIS OF QUARDATURE HYBRIDS

A distributed quadrature hybrid as shown in Fig. 1 consists of two pairs of transmission line segments (series and shunt arms) with characteristic impedance (Z_{01}, Z_{02}) and length (ℓ_1, ℓ_2). To analyze this four-port network, even-odd mode analysis is employed to bisect the circuit due to its symmetric property. Based on the analysis, a quadrature hybrid can only be matched at all ports if the following conditions stand:

$$\tan(\beta\ell_2/2) = \pm 1 \qquad (1)$$

$$\cot\beta\ell_1 = 0 \qquad (2)$$

$$(Z_0/Z_{01})^2 = (Z_0/Z_{02})^2 + 1. \qquad (3)$$



Series arms (Z_{01}, $\beta\ell_1$): T_{1A}, T_{1B}
Shunt arms (Z_{02}, $\beta\ell_2$): T_{2A}, T_{2B}

Fig.1 The branch-line quadrature hybrid.

From (1) and (2), the electric length of the series and the shunt arms can be either 90° or 270°. Therefore, four different prototypes derived from the electric length conditions have been analyzed separately to examine the full extent of the quadrature hybrid design. Assuming $y_1 = Z_0/Z_{01}$ and $y_2 = Z_0/Z_{02}$, the coupling at the output ports is derived as

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$$S_{21} = \frac{1}{2}(T_{even} + T_{odd}) = \frac{\pm j y_1}{1 + y_2^2} \qquad (4)$$

$$S_{31} = \frac{1}{2}(T_{even} - T_{odd}) = \frac{\pm y_1 y_2}{1 + y_2^2} \qquad (5)$$

for $\beta\ell_1 = \begin{pmatrix} \lambda/4 \\ 3\lambda/4 \end{pmatrix} \beta\ell_2 = \begin{pmatrix} \lambda/4 \\ 3\lambda/4 \end{pmatrix}$, respectively.

For a coupling ratio $k = |S_{31}/S_{21}| = y_2$ at the output ports, the characteristic impedances are given by $Z_{02} = \frac{Z_0}{k}$ and $Z_{01} = \sqrt{\frac{Z_{02}^2 Z_0^2}{Z_{02}^2 + Z_0^2}}$. In addition, a phase difference of 90° can be obtained between the port 2 and port 3, where port 3 is leading in phase for $\beta\ell_2 = 3\lambda/4$, and lagging for $\beta\ell_2 = \lambda/4$.

III. Design Of Lumped Quardature Hybrids

A transmission line segment can be replaced by a lumped T or π network at its center frequency. By applying the lumped equivalent networks in the four distributed prototypes, sixteen lumped quadrature hybrid designs are possible.

The sixteen lumped designs provide the flexibility for circuit implementation, and the choice is determined based on the application requirement and the availability of the lumped components at the operating frequencies.

IV. Experimental Results And Discussion

After computer simulations, four out of the sixteen designs are chosen for fabrication and characterization; the schematics of these circuits are shown in Fig. 2. Only π networks have been employed to replace the transmission line segments because this permits the shunt lumped components at the ports to be combined into a single element. This lowers the device count which simplifies the design, decreases the circuit size, and decreases the insertion loss.

The micromachined technology developed to improve the Q-factor and the resonant frequency of lumped passive components has been employed to fabricate the hybrid circuits. Figure 3 shows the photomicrograph and the chip size of the fabricated micromachined hybrids. To verify the circuit performance, on-wafer probing S-parameter measurement has been performed on the quadrature hybrids using HP8510B network analyzer. Figure 4 shows the measured S-parameters of the fabricated hybrid circuits.

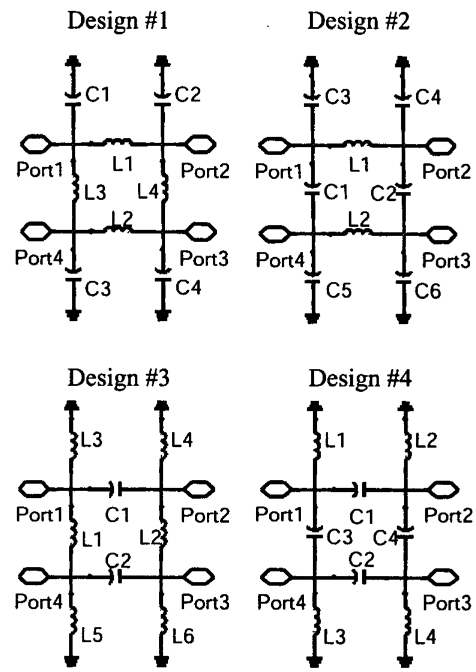

Fig. 2 The schematic of the lumped quadrature hybrids.

In design #1, the series and shunt arms of the branch-line hybrid are replaced by low-pass π networks, resulting in a low-pass frequency response for the through and coupling ports. Therefore, a flat coupling characteristics at the output ports can be obtained with a phase difference of 90°. The bandwidth defined by 15 dB return loss is 6.5%, and an isolation of 20 dB is provided at the center frequency. As shown in the schematic of design #2, series and shunt arms are replaced by low-pass and high-pass π networks, respectively, resulting in a low-pass characteristics for S_{21} and a band-pass one for S_{31}. Ideally, S_{21} and S_{31} should be equal in magnitude (-3 dB) with a phase difference of 90° at the center frequency. However, the measurement shows an extra insertion loss of 1.5 dB and a phase deviation of 13° due to the parasitics of the lumped components. By replacing the series and the shunt arms with high-pass and low-pass π networks, respectively, a high-pass S_{21} and a band-pass S_{31} can be obtained in design #3. Compared with the performance of design #2, similar phase deviation and insertion losses are observed in the S-parameter measurement. In design #4, all transmission line segments in the branch-line hybrid are replaced by high-pass π networks as can be seen in the schematic. Therefore, both S_{21} and S_{31} show high-pass characteristics in frequency domain. At the center frequency of 8.5 GHz, the insertion losses of S_{21} and S_{31} are 5.0 and 5.3 dB, respective, with a phase difference of 90°.

Table 1. The S-parameter measurement of the fabricated 90° hybrids at 8.5 GHz.

Design	#1	#2	#3	#4
Return loss (S_{11}[dB])	18	19	19	18
Insertion loss (S_{21}[dB])	4.6	4.9	4.5	5.0
Insertion loss (S_{31}[dB])	5.2	4.3	4.2	5.3
Isolation (S_{41}[dB])	20	18	19	21
Phase (S_{31}/ S_{21})	-90°	77°	-77°	89°
Bandwidth (15 dB return loss [%])	6.5	10	11	6.5

To summarize the performance of the fabricated quadrature hybrids, the S-parameter measurements at the center frequency of 8.5 GHz are listed in Table 1. By applying the micromachined technology for passive components, X-band lumped quadrature hybrids have been demonstrated for the first time. The fabricated circuits exhibit superior performance to other lumped designs [1]-[3] with lower operating frequencies. Moreover, compared with distributed designs on Si substrate, chip size reduction up to two order of magnitude has been achieved. Each design of the lumped quadrature hybrids has its unique characteristics in terms of frequency response, insertion losses, isolation, bandwidth and phase difference. Therefore, the choice can be made based on the requirement of the circuit applications.

V. CONCLUSION

A systematic analysis and design technique has been developed to explore the lumped quadrature hybrids in full extent. High-performance quadrature hybrids have been fabricated with a micromachined technology, causing a significant reduction in chip size compared with distributed designs at X-band. This technique can also be applied for distributed microwave circuits such as Wilkinson power dividers, 180° hybrids and impedance transformers to reduce the chip size in MMIC applications at frequencies up to K-band range.

ACKNOWLEDGEMENT

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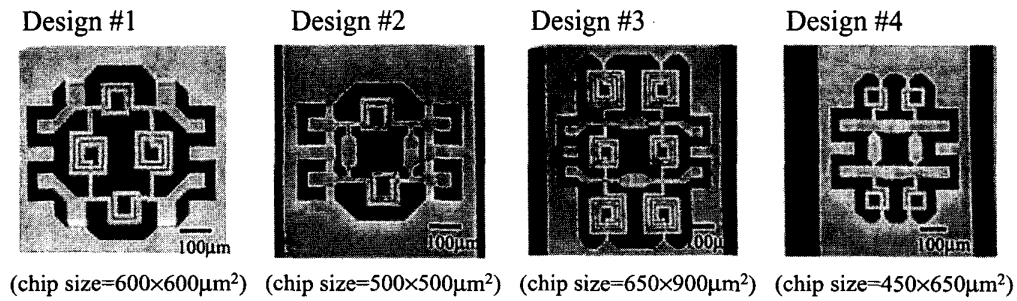

Fig. 3 The photomicrograph of the lumped quadrature designs.

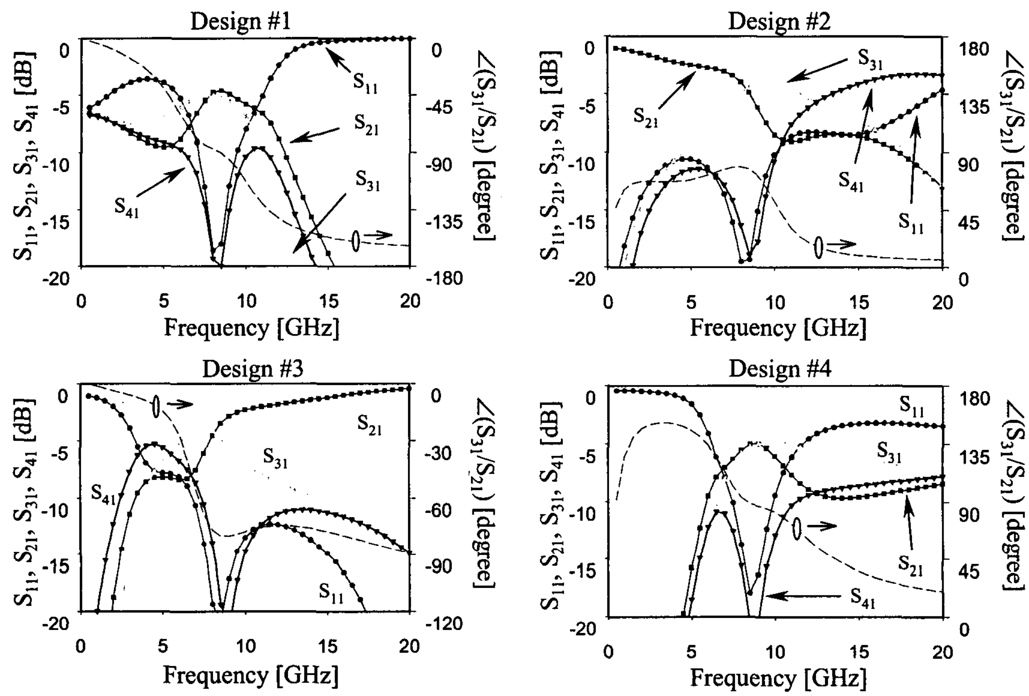

Fig. 4 The measured S-parameters of the lumped quadrature designs.