Megalithic Microwave Signal Processing for Phased-Array Beam Forming and Steering

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Abstract- Microwave signal processing (MSP) architecture is presented for active phased array beam forming and steering. A large scale network, comprising 63 power dividers and 32 pairs of orthogonal phase-amplitude controllers, has been successfully developed in a single GaAs MMIC. This megalithic chip could mark an epoch in phased-array antenna systems.

I. Introduction

Global and regional access satellite communication systems have recently been proposed with prospective multiple-beam LEO or GEO satellites. The number of satellite beams is predicted to be increasing year by year for frequency reuse and growing traffic demand. To radiate high power multiple beams, the approach of an active phased array with spatial power combining is a viable solution. In this approach, the beam steering is expected to provide:

1) point each beam precisely to the target area against possible deviations in all components of the array system and satellite attitude
2) form nulls exactly onto the neighboring area where the frequency reuse could create problems
3) provide reconfiguration in the case of failure for any beam

Precise beam and null pointing becomes more serious especially in case of a high-gain reflector antenna system[1]. To perform adaptive beam steering, digital beam forming (DBF) or digital signal processing (DSP) has been employed in some practical systems[2][3]. In case of multi-carrier systems like satellite transponders, however, the DSP dissipates high dc power as the number of the carriers increases. It also requires dozens of high-speed and high-resolution digital-to-analog converters (DACs).
Another approach to steer the beam is to introduce control circuits[4]-[9] in the analog beam forming network (BFN). This paper presents a direct microwave signal processing (MSP) architecture for active phased array beam forming and steering. A record-breaking megalithic integration is described along with a highly-dense constituent circuit topologies.

II. BFN Architecture

A BFN must be equipped with the proportional number of power dividers, variable phase shifters, and attenuators to the radiator elements. To accomplish monolithic integration of this huge scale circuit, a new BFN architecture is presented as shown in Fig.1, featuring a 64-way pyramidal power distribution and phase/amplitude control without employing any conventional phase shifters. Full 360-degree phase is generated on a vector-synthetic principle by orthogonally coupled twin attenuators. The proposed circuit topologies to carry out this architecture are the pyramidally-cascadable power divider (PcPD) and the phase-invertible variable attenuator (PiVA).

III. Pyramidally-Cascadable Power Divider (PcPD)

The PcPD consists of only one inductor, two capacitors and one resistor, as shown in Fig.2. It functions as a 3 dB power divider in which the two output ports are isolated from each other. To reduce circuit space, the configuration is over simplified so that each port does not match to a real impedance. In spite of this over simplification, the input and output impedances are complex conjugate match when $6L = CR^2$ [7]. This relationship means the I/O impedance is iterated at each stage, which provides cascade connections without any inter-stage matching networks. This design principle enables one to realize a 2^n-way pyramidal power distribution in a very compact MMIC area.

IV. Phase-Invertible Variable Attenuator (PiVA)

The PiVA scheme, shown in Fig.3, utilizes twin cold FETs interlocked by a single control wire. When the gate width is designed to satisfy the relationship of

$$R_{ds,\,min} \times R_{ds,\,max} = Z_o^2 ,$$

output phase can be inverted +/-90 degrees in addition to continuously varying the output amplitude[7]. This cell requires only one control signal, hence it is very space efficient. Based upon the vector-synthetic principle, arbitrary phase and amplitude is generated by coupling orthogonally a pair of PiVA cells.

V. Prototype GaAs MMIC

A prototype BFN is fabricated on a single 11 mm x 13 mm GaAs chip as shown in Fig.4, consisting of one rf input port, 32 rf output ports, 32 pairs of control dc terminals, and more than one thousand elements inside. The megalithic BFN performance is measured at the S-band satellite communication frequencies using a wafer probe station. The expected 360-degree phase was successfully observed and depicted with the step of 15 degrees in Fig.5. In each of the 24 states, vector deviations exhibited are within 0.38 dB r.m.s. and 2.8 deg r.m.s. over the bandwidth of 20 MHz at 2.5 GHz. This performance is suitable for onboard active phased array applications. The designed BFN is fully reciprocal so that it can be applied not only to transmitters but also receivers. Since this design is both space efficient and does not generate heat, it could be applied to multi-beam BFNs by piling up the BFN chips for each beam control layer.

VI. Conclusion

Novel lumped-constant circuit topologies are presented for high density integration. A huge scale circuit, being fully functional as an entire beam forming and steering network, has been designed and fabricated in a single GaAs MMIC chip. This development could be a major step to realization of "pseudo" LSI signal processing directly at microwave frequencies.

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