Active Transmitarray Submodule for K/Ka Band Satcom Applications

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Abstract—A novel concept for an active transmitarray architecture for K/Ka Band Satcom applications is presented. The highly-integrated antenna system is based on planar multilayer arrangement covering both Satcom frequency bands for uplink at 30 GHz and downlink at 20 GHz. To verify the proposed manifold approach, the individual components and a first active dual-band transmitarray submodule enhanced by a multi-functional SiGe BiCMOS MMIC have been realized and measured successfully.

I. INTRODUCTION

The continuously growing demand for high data rate links has become one of the main driver for broadband satellite communication (Satcom) systems. Moving to higher operational frequencies at K/Ka band mainly addresses higher channel capacities for a large variety of end users and miniaturized antenna system [1]. In order to keep established Satcom links while moving, planar and lightweight architectures for phased array systems are of major importance. A typical approach to meet the Satcom specifications employs two separated steerable antenna systems for transmit and receive mode [2]. In contrast to regular arrays, an aperiodic array for the transmit antennas results in a reduced number of uniformly fed elements without degrading the radiation diagram in terms of side lobe and grating lobe levels [3]. First studies of an active dual-band transmitarray in a thinned element configuration are presented. Therefore, the receive elements are placed in between the irregular lattice of the transmit array for a more compact overall system. In addition, the proposed flexible transceiver architecture is also applicable for the use in overlapped subarrays operating at 20 GHz and 30 GHz, respectively [4], [5].

II. ARRAY ARCHITECTURE

The proposed architecture for the active dual-band transceiver array at K/Ka band is based on the transmitarray concept [6], [7]. According to the Satcom specifications the frequency bands for bi-directional data links are from 19.7 GHz to 21.0 GHz for downlink and 29.5 GHz to 30.8 GHz for uplink, respectively. The schematic cross section of the array architecture is illustrated in Fig. 1. Considering the array in transmit mode in the Ka band (dashed rays), the feed antenna distributes the RF signal by a space-fed arrangement to the dual-band antenna elements where the signal is guided to the multi-functional ICs. In particular for larger arrays the efficiency increases and tends to a more flexible and scalable design due to the absence of a printed RF distribution network to the ICs [8]. In the active circuits amplitude and phased adjustments are performed to synthesize the required transmit diagram. Subsequently, the modified RF signal is carried to the individual antenna elements on the top side of the array

Fig. 1. Schematic cross section of the active dual-band transmitarray.

for re-emission of the electromagnetic wave. The operation principle of the presented transmitarray architecture in the receive case works in the same manner as for the transmit case. However, the dual-band antenna element pointing to the feed antenna uses orthogonal polarizations for both frequency bands to minimize its area consumption.

The layer stack up of the novel dual-band transmitarray configuration is given in Fig. 2 and can be subdivided into 3 functional parts. The lower multilayer PCB with the orthogonal-mode dual-frequency patch antennas is part of the distribution network and carries also bias and control lines to the active circuits embedded on the backside of the board. The chip [9] is based on a state-of-the-art SiGe BiCMOS

Fig. 2. Layer stackup of the proposed active transmitarray submodule composed with the dielectric materials ①,⑤: Rogers RT Duroid 5870 ($h=0.787$ mm, $\epsilon_r=2.33$); ②,④: Rogers RO3003 ($h=0.127$ mm, $\epsilon_r=3$); ③: Arlon AD300 ($h=2.17$ mm, $\epsilon_r=3$).

process from IHP Microelectronics (IHP SG25 BiCMOS). The monolithic integration of analog and digital circuitry in one

multi-functional IC is essential to meet the space constraints in highly-integrated phased array systems. The SiGe MMIC includes four transmit and two receive channels enhanced by a digital i²c bus interface for serial control of all IC functions. Each receive channel comprises a low-noise amplifier (LNA) followed by a vector modulator (VM), and the transmit channel is cascaded with a vector modulator, a driver amplifier (DA) and a power amplifier (PA).

The antenna elements on the upper board are connected with the lower one by vertical board-to-board transitions presented in Section IV. According to the number of available channels per MMIC the transmitarray submodule includes two patch antennas for downlink and four patch antennas for uplink. For the first tests, a simplified arrangement of the individual antenna elements within the submodule using a skewed submodule lattice has been considered (see Fig. 3). The

Fig. 3. Exemplary dual-band submodule lattice of the proposed active transmitarray for K/Ka band ($l_{uc}=5$ mm).

simulated radiation diagrams of the dual-band transmitarray using this exemplary configuration is presented in Fig. 4. As expected, the aperiodic array lattice with uniform excitations results in a significantly decrease of the side lobe levels compared to a periodic lattice. Moreover, the grating lobe levels are noticeable lower than for an equally spaced array but needs to be optimized further.

Fig. 4. Simulated radiation diagrams of a dual-band transmitarray with 21x32 submodules.

III. DUAL-BAND MICROSTRIP ANTENNA

As mentioned before, the dual-band antenna is realized as a rectangular microstrip patch. According to the proposed transmitarray architecture the antenna element, as a part of the distribution network, has to cover both operational bands for downlink (19.7 GHz-21.0 GHz) and uplink (29.5 GHz-30.8 GHz). An inclined slot in the ground plane is used to excite the fundamental resonances TM_{100} and TM_{010} of the microstrip patch with a single microstrip feed line [10], [11]. This feeding method results in a very compact and simple antenna configuration to operate in two frequency bands using orthogonal polarizations. In Fig. 5 the exploded view and the

Fig. 5. Dual-band microstrip patch antenna element with the parameters: $l_{patch,x}=2.53$ mm, $l_{patch,y}=4.17$ mm, $l_{slot1}=0.9$ mm, $l_{slot2}=2.4$ mm, $w_{slot1}=0.3$ mm, $\varphi=65^\circ$, $w_{msl}=0.3$ mm, $l_{stub}=0.7$ mm.

parameters of the dual-band microstrip antenna are shown. The parametric study and optimization of the dual-band antenna element have been carried out using Ansys HFSS [12]. The measured and simulated reflection coefficients for the presented dual-band aperture coupled patch antenna are depicted in Fig. 6. In order to de-embed the surface mount coaxial connector from the measurement results a time domain gating starting at $t=170$ ps after the calibration plane was applied. The measured (de-embedded) reflection coefficient shows excellent agreement to the simulations and remains below -10 dB in the frequency range from 19.17 GHz to 21.56 GHz and from 27.38 GHz to 32.43 GHz, respectively.

Fig. 6. Measured and simulated reflection coefficient of the dual-band microstrip antenna.

IV. VERTICAL BOARD-TO-BOARD TRANSITION

Fig. 7 illustrates the proposed board-to-board transition realized as a vertical three-wire transmission line. Therefore, the centered signal via and the two ground vias are processed within the intermediate RF laminate ③ (see Fig. 2). In

Fig. 7. Vertical board-to-board transition element with the parameters: $w_{msl}=0.3$ mm, $d_{pad}=0.6$ mm, $d_{via}=0.4$ mm, $d_{gvia}=0.7$ mm, $d_{slot}=1.2$ mm, $t_{grid}=1$ mm.

a different way from recent investigations [13] almost the entire dielectric material on ③ is removed by milling to form the required cavity for the chip integration. Hence, only a narrow dielectric grid with a thickness of $t_{grid}=1$ mm is kept to carry the three vias (see Fig. 7a). Subsequently, the respective microstrip lines on L3/L6 of the upper and lower multilayer PCB are joined together with the intermediate board by soldering. Additional cutouts in the ground planes (L2/L7) with a diameter $d_{slot}=1.2$ mm are used to further enhance its RF performance, especially at higher frequencies.

Two vertical board-to-board transitions have been fabricated and assembled successfully in a back-to-back configuration. Two different microstrip delay lines were realized to obtain the de-embedded S-parameter results of a single microstrip-to-microstrip transition (see Fig. 8). The

Fig. 8. Photograph of the back-to-back configuration of the proposed vertical board-to-board transition.

measured and simulated S-parameters of the proposed transmission structure are presented in Fig. 9. In the intended frequency bands for downlink (19.7 GHz-21.0 GHz) and uplink (29.5 GHz-30.8 GHz) the measured reflection coefficient is below -11.4 dB. The measured transmission coefficient is slightly lower compared to the simulation results and has its minimum of -1.35 dB in the upper operational band at 30.8 GHz.

Fig. 9. Measured (de-embedded) and simulated S-parameters of the single vertical board-to-board transition.

V. ACTIVE DUAL-BAND TRANSMITARRAY SUBMODULE

After the successful characterization of the individual components presented in the previous sections, the PCB manifold of the novel dual-band transmitarray submodule has been fabricated. In the next step, the dual-band MMIC has been glued into the cavity of the lower multilayer PCB and connected to layer L6 by wire bonding (see Fig. 2). Since the multi-functional MMIC can be fully controlled via a digital i²c bus interface only two wires – SCL (clock) and SDATA (bi-directional data) – are required for communication. Moreover, three wires are provided for the power supply (3.3V/GND/2.5V). An initial check of the MMIC was conducted to verify its general functionality. Finally, the dielectric grid including 6 vertical transitions and the K/Ka band patch antennas are joined together with the lower multilayer PCB by soldering. A photograph of the novel active transmitarray submodule for K/Ka band is depicted in Fig. 10.

Fig. 10. Photograph of the proposed dual-band transmitarray submodule.

Since the dual-band transmitarray submodule exhibits fabrication and assembling tolerances, a calibration of the 4 TX and 2 RX channels is prerequisite for their proper operation. The calibration procedure was performed in the near field

based on the proposed method in [14]. Once the transmitarray submodule has been fully calibrated, the amplitude and phase values of the individual channels can be precisely adjusted to synthesize the intended far field pattern. Fig. 11 illustrates the radiation diagram of the proposed dual-band transmitarray at 20 GHz in both principle planes using the same amplitude and phase settings for the two receive antennas.

Fig. 11. Measured and simulated radiation diagram of the proposed dual-band transmitarray submodule at 20 GHz.

In the same manner as for the receive channels, equal amplitude and phase values are set to all transmit elements. The measured and simulated radiation diagram of the four transmit antennas at 30 GHz is presented in Fig. 12. In both operational frequency bands at K/Ka band a very good agreement between the experimental results and the simulated far field patterns can be observed.

Fig. 12. Measured and simulated radiation diagram of the proposed dual-band transmitarray submodule at 30 GHz.

VI. CONCLUSION

A novel dual-band transmitarray architecture for Satcom applications at K/Ka band has been presented. The individual components required for the transmitarray submodule were fabricated and characterized. The presented dual-band

microstrip antenna shows excellent agreement between the measured and simulated reflection coefficient in the projected frequencies bands. As the key component for that approach, the proposed vertical board-to-board transition was realized successfully in a back-to-back configuration. The measured reflections coefficient remains below -11.4 dB and the insertion loss is better than 1.35 dB in both frequencies bands. The first prototype of the active dual-band transmitarray submodule has been assembled and first measurements demonstrate already its excellent functionality. The potential to use the presented dual-band transmitarray architecture also in the context of aperiodic arrays has been briefly shown. However, these aspects will be elaborated in future work.

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