

AN ACTIVE INTEGRATED KU-BAND ANTENNA BREADBOARD FOR DIGITAL BEAMFORMING SYSTEMS

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ABSTRACT

This contribution reports on an active integrated 8-element linear antenna array for receiving at Ku-Band frequencies suitable for an application in a 8-channel digital beamforming system. The array configuration integrates aperture coupled stacked microstrip patches with the necessary active multichannel receive circuitry for a first downconversion to L-Band frequencies. Each branch of the system consists of a LNA and a printed filter succeeded by an active mixer. To provide the 8 LO-signals for the mixing stages, a planar distribution network was designed. Reliable and temperature stable operation of the complete antenna frontend is ensured by an active bias network. A directional coupler behind each radiating element allows the injection of a test signal into each receiving branch for calibration purposes. All the aforementioned frontend components are integrated in a multilayer RT/duroid substrate board, that consists of 4 layers. The material provides a reasonable compromise between the performance of the radiating elements, side conditions imposed by the integration point of view and the available technology in our institute. Nevertheless, the selection of other materials in conjunction with unpackaged MMICs would lead to an improved packaging of the frontend and form a highly integrated active antenna array, provided that an appropriate and sophisticated manufacturing process is available.

INTRODUCTION

The investigation and application of digital beamforming (DBF) techniques has been mainly restricted to lower frequency bands in the past. Due to the increasing demand for more sophisticated antennas for a broad range of challenging applications especially at higher frequencies, the establishment of this kind of antenna system becomes attractive. To address this situation and to study functional aspects of DBF, we developed a complete system operating in the Ku-Band.

Besides a very high performance signal processing capability one of the most crucial parts of a DBF antenna system is an appropriate RF frontend. At higher frequencies, several problems are associated with classical antenna elements and their feeding technique, e.g. a connector system inherits a high reflection coefficient and an unacceptable insertion loss. For this reason an integrated approach comprising a radiating element and an amplifier may be the preferable solution for a practical implementation. Hence, in the conventional DBF architecture every system branch has to consist of its associated circuitry, which leads to a completely integrated active array frontend. Furthermore this architecture also avoids the losses in conventional array combining networks occurring prior to the first LNA, that contribute directly to the overall system noise temperature.

At Ku-Band frequencies there already remains very limited space associated to every element in an antenna array. This causes several severe problems with the packaging of the active components, especially in 2-dimensional arrays, that demand for a highly sophisticated technology and an expensive manufacturing process. Defying this difficult starting point, we developed an integrated solution for a linear array based on conventional microwave transistors. The configuration consists of a single down-conversion stage for each antenna element build up of LNA, filter and active mixer. Further building blocks are a LO-distribution network, active biasing circuitry for temperature stable operation and a calibration network to address the inevitable amplitude and phase differences in the separate receive channels.

SINGLE ELEMENT ACTIVE RECEIVING ANTENNA

Prior to the realisation of the complete array system, we developed all parts of the active receiving chain separately. In the second step the integration of these parts with a single antenna element took place. The succeeding implementation of the complete antenna array of course had a great impact on this development phase.

The design goal was to realise an instantaneous receiving bandwidth of the frontend of 400 MHz and to provide a second band around 15 GHz for a later implementation of a transmit branch. In addition to the radiating element, each receiving branch of the array consists of a calibration coupler, a LNA, a printed filter and an active mixer. These components are described in further detail in the following paragraphs. A schematical circuit diagram of the configuration is depicted in Fig. 2.

Radiating Element

As a suitable antenna element for an integration with active circuitry, we use the aperture-coupled stacked microstrip patch arrangement depicted in Fig. 1. In literature, e.g. [1], this antenna is known as wide band element with usable bandwidths of 25 percent and more. The bandwidth strongly depends on the used substrate materials, in general it is of course favourable to use a very low dielectric constant material and rather thick substrates. To comply with different aspects contributed by the integration point of view, we chose a configuration of four 0.5mm thick substrates with a dielectric constant of 2.33, in which two of the substrates are located between the patches. This lead us to the result shown in Fig. 3. The antenna element exhibits two separate bands with more than 6% bandwidth for return loss better than 10 dB each. With our choice of materials, it is very difficult to merge these two subbands and to achieve the true broadband performance. Nevertheless these results are quite sufficient for our application and provide a reasonable compromise between the RF performance and different implementation driven side conditions.

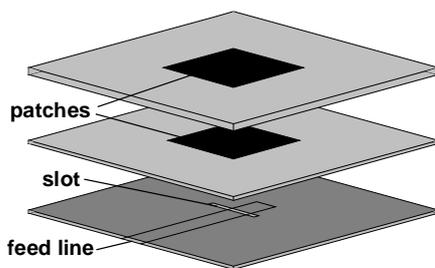


Fig. 1. Aperture-coupled stacked patch antenna

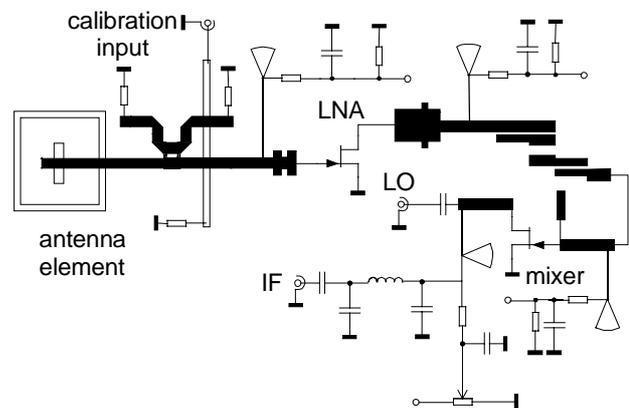


Fig.2. Schematical circuit diagram of the active receiving antenna element

Calibration Coupler

To achieve a high quality DBF system and successful operation, an opportunity for a system calibration is needed to address the differences in the amplitude and phase responses of the receiving branches. In our system, a calibration network similar to the solution in [2] is used. It enables the injection of a test signal directly behind each radiating element of the array. This is realised by the implementation of a directional coupler with its secondary line fed via a single hole coupler by a stripline located between lower substrate layers. The directional coupler is realised with interdigital capacitors at either ends of the coupling zone to improve directivity. The measured directivity and insertion loss of the main line were 21 dB and 0.5 dB respectively, which are indeed good values for a coupler in this technology. The functionality of the complete network in the frontend is to be combined with an additional far field source calibration procedure to account for mutual coupling in the array and to provide the desired accuracy of the system.

Active Receiver Components

The active receiver components were built up with conventional microwave transistors, that are matched by printed networks. The developed LNA exhibits a typical noise figure of about 0.8 dB and a gain of approx. 12.5 dB. The mixer has a conversion gain of typical -3 dB and a noise figure of approx. 5.9 dB. The reproducibility of the LNA parameters

with different transistors was quite good. We noticed a standard deviation of the gain and noise figure of only 0.8 dB and 0.2 dB respectively. In this prospect the mixer is much more critical, which lead us to the implementation of an adjustable resistor in the bias path of each mixer in the complete array frontend. Nevertheless, based on a reliable LNA component, it may be possible to skip this expenditure.

With an insertion loss of approx. 0.5 dB for the calibration coupler and 2.8 dB for the bandpass filter, we result in an overall gain of 6.2 dB and a cascaded noise figure of 2.4 dB. These values were also confirmed by experiment. As there is still a potential in the rather poor gain of the mixer, an additional improvement is still possible.

The necessary bias currents for the elements are provided by an active bias network, that ensures a reliable and temperature stable operation of the components.

Implementation and Measurement

After the prescribed development, we integrated the different receiver components with the radiating element. To take profit of the comfort of a conventional antenna measurement range, we omitted the mixer in this implementation. The layer configuration of this integrated antenna, that is in fact identical to the solution for the complete array frontend, is depicted in Fig. 5.

Fig. 4 shows the radiation pattern of the single element active receiving antenna referenced to the maximum measured value of the passive element. The curves indicate an additional gain of the active antenna of approx. 9 dB. The deviations of the passive and active pattern at larger angles are due to the coax – stripline – transitions for the calibration signal inputs located on either side of the antenna substrate board.

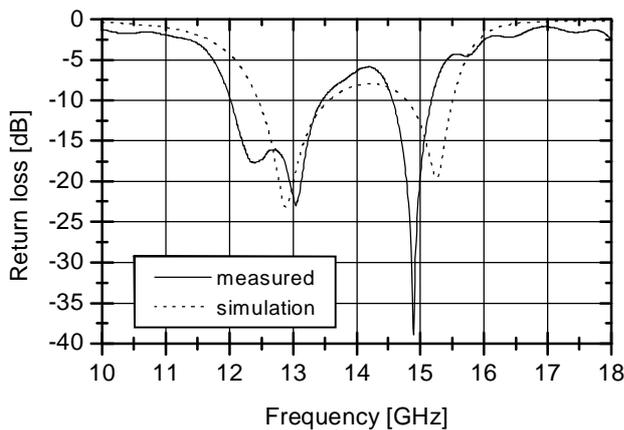


Fig. 3. Measured and simulated return loss of the passive antenna element

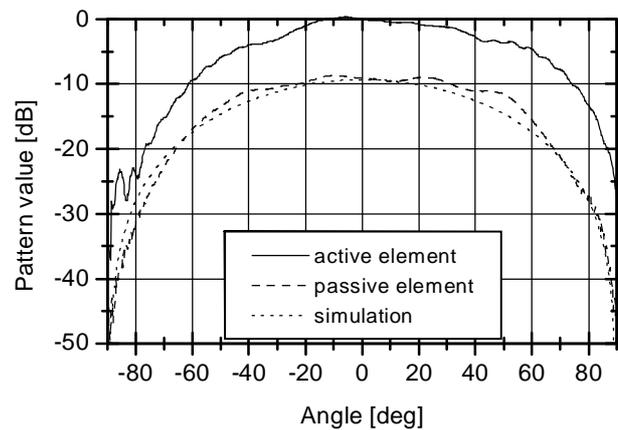


Fig. 4. Measured and simulated radiation patterns of the single element active antenna

THE COMPLETE ANTENNA FRONTEND

Based on the single element configuration, the complete active antenna array was built up of 8 elements with a separation of 0.56λ at midband. This keeps the grating lobes out of visible space for scanning angles up to approx. 60° . Within the substrate configuration depicted in Fig. 5, that is identical with the single element antenna structure, we noticed mutual coupling levels of neighboured elements around 15 dB in theory and experiment and of course lower levels for elements with a greater separation. Based on these values, only a moderate deformation of the single element active pattern in the array environment occurs. Nevertheless, the mutual coupling has to be accounted for when attempting to achieve high quality patterns or applying non-linear signal processing techniques to the output signals of the DBF system. For this reason, a calibration procedure based on far field signals is necessary, that can also be combined with the operability of the calibration network.

To supply the mixing stages with the necessary LO-signals, a printed 1:8-power-distribution network consisting of a 1:2- and two 1:4-power dividers was designed. The dividers are carried out as circular sector-shaped components [3]. The complete network can be seen on the right side in Fig. 6. It inherits an insertion loss of 1.1 dB per branch above the theoretical split loss of 9 dB. The amplitude and phase balances are ± 0.3 dB and $\pm 9.5^\circ$ respectively.

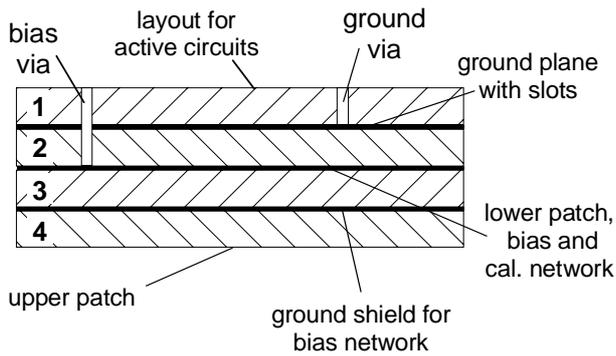


Fig. 5. Substrate configuration of the 4-layer active antenna array

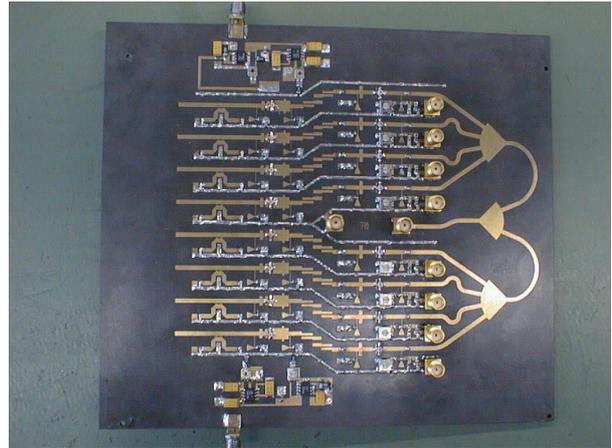


Fig. 6. Photograph of the fully assembled active antenna array board

Fig. 6 shows a photograph of the fully assembled active antenna array board. The radiating elements are located on the back side left hand of the picture. On the top and bottom we have the bias networks for the LNAs and the mixers as well as the coax – stripline – connectors for the injection of the calibration signals. The overall performance of the single branches are measured in conjunction with the whole DBF system, which is not a part of this contribution. However, in comparison to the single element antenna, the characteristics of the branches are mainly affected by the mutual coupling in the array. During the measurements, the coupling between the active circuits on the board was found to be neglectable.

The whole implementation occupies a rather large space, thus in this stage it is not appropriate for the realisation of a 2-dimensional array. Nevertheless, a considerable miniaturisation of the whole frontend is possible by choosing a substrate material with a high dielectric constant as carrier for the active circuits. In conjunction with the usage of unpacked MMICs, this would lead to a highly integrated active antenna array, of course based on a highly sophisticated manufacturing process.

CONCLUSION

An active integrated Ku-Band antenna breadboard for an 8-channel DBF system was developed. It combines the radiating elements and the receiver components for a first signal downconversion to L-Band frequencies. Additional features are a 1:8 LO-distribution network as well as an integrated calibration network and active biasing to achieve accurate system operation. The performance was proofed by measurements.

Being a breadboard, our rather conventional integrated implementation realises the first important step towards a highly integrated and miniaturised active antenna array. Moreover it suits our needs for the investigation of functional aspects of DBF at higher frequencies.

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