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Citation for published version (APA):

Zamanifekri, A., Lu, C., Visser, H. J., Sanders, P., Matters - Kammerer, M., Geurts, M., Baltus, P. G. M., & Smolders, A. B. (2017). An active Ka-band shared aperture antenna with 50 dB isolation for satellite communication. *IEEE Antennas and Wireless Propagation Letters*, 16, 2042-2045. [7903659].
<https://doi.org/10.1109/LAWP.2017.2695258>

Document license:
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DOI:
[10.1109/LAWP.2017.2695258](https://doi.org/10.1109/LAWP.2017.2695258)

Document status and date:
Published: 01/01/2017

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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An Active Ka-Band Shared-Aperture Antenna With 50 dB Isolation for Satellite Communication

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Abstract—An active hybrid shared-aperture concept (employing both active and passive circuits) is presented. This active shared aperture realizes the required isolation level of 48 dB between transmit (TX) (30 GHz) and receive (RX) (20 GHz) channels of a ground terminal for two-way satellite communication. It can be applied in very small aperture terminals. The dual-frequency shared aperture can be used as a building block for a linearly or circularly polarized phased-array feed in a focal-plane array system. It includes a 20-GHz low-noise amplifier with on-chip notch filtering realized in a 0.25- μm SiGe:C BiCMOS technology. The on-chip filter achieves 30 dB of attenuation at 30 GHz with only 0.4 dB noise figure degradation. The isolation is further enhanced by a novel dual-frequency shared-aperture concept based on defected ground structures in the printed circuit board. Experimental results from the prototype show an overall isolation between TX and RX channel of more than 50 dB at 30 GHz.

Index Terms—Dual-polarized antennas, filtering antenna, satellite communication, shared-aperture antenna.

I. INTRODUCTION

Focal plane arrays (FPAs) appear to be a very interesting concept to realize two-way satellite communication [1] since it combines a low-cost and high-efficiency reflector with the ability for electronic beam steering within a limited scan range. Different from phased arrays, an FPA requires both amplitude and phase control of each of the array elements to achieve smooth beam steering. For very small aperture terminals (VSAT), beam switching could also be applied. One of the main problems in a full-duplex system is the required isolation between the transmit (TX) and receive (RX) channels. In VSAT, the RX channel operates from 18 to 22 GHz, and the TX channel is in the 29.4–30-GHz band. As compared to traditional feed horns, the TX-to-RX isolation is much more difficult to realize for phased-array feeds since the required isolation should be

applied at the level of individual array elements, typically using an array grid spacing between $0.5\lambda_0$ and $0.7\lambda_0$ at 30 GHz, where λ_0 is the wavelength in free space. Therefore, a cost-effective integrated solution is required that takes full benefit of the filtering capabilities of printed antennas and on-chip filters. This solution should be based on mainstream printed circuit board (PCB) and (Bi-) CMOS semiconductor technologies. Traditionally, high-quality filters and duplexers (e.g., waveguide filters) are used to suppress out-of-band interference at the input of the receiver [2], [3]. These filters, however, are expensive and relatively bulky and can therefore not be used in highly integrated phased-array feeds for low-cost applications. An alternative in full-duplex systems is to use an analog cancellation technique instead of a filter approach [4]. This technique utilizes the fact that the transmitter signal properties are locally known in transceiver systems. One can use this knowledge and generate a replica of the interference signal at the input of the receiver. By using proper complex coefficients of the interference signal, it is possible to cancel the strong interference signal. However, this approach suffers from a high insertion loss and, as a result, a poor noise figure.

In order to achieve a compact solution, we propose to use a shared-aperture phased-array concept that can be used to realize transmission at 30 GHz and reception at 20 GHz, simultaneously. A high isolation between the TX and RX channels is achieved by embedding the bandpass filter within the antenna. Additional isolation is provided by combining the filtering shared aperture with a low-noise amplifier (LNA) that includes on-chip filtering. The proposed hybrid solution can be used to realize linearly or circularly polarized FPAs and provides more than 50 dB isolation between transmitter and receiver at 30 GHz, which is comparable to more bulky and expensive state-of-art waveguide-based filters. Our highly integrated hybrid concept allows us to use low-cost standard PCB technology and low-cost BiCMOS silicon technology.

II. SYSTEM ANALYSIS AND REQUIREMENTS

The system figure of merit in satellite communication is given by the G/T ratio

$$\frac{G}{T} = \frac{G}{\eta T_a + T_0(1 - \eta) + T_{RX}} \quad (1)$$

where G is the antenna gain, T is the equivalent noise temperature of the total system, T_a is the antenna noise temperature, T_0 is the environmental temperature, η is the antenna radiation efficiency, and T_{RX} is the receiver effective noise temperature. The latter includes a contribution from the power amplifier (PA)

Manuscript received February 16, 2016; revised March 22, 2017; accepted April 13, 2017. Date of publication April 18, 2017; date of current version July 24, 2017. (Corresponding author: Adrianus Bart Smolders.)

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Digital Object Identifier 10.1109/LAWP.2017.2695258

TABLE I
NOISE MEASUREMENTS AT 20 GHz WITH SEVERAL 30-GHz AMPLIFIERS

Parameter	TGA4509 [5]	TGA4529 [6]	TGA6432 [7]
Saturated power (P_{sat})	31 dBm	31 dBm	34 dBm
Noise power density	-157 dBm/Hz	-155 dBm/Hz	-170 dBm/Hz
Noise temperature T_{PA}	14 458 K	22 915 K	724 K

output

$$T_{\text{RX}} = 290 (F_{\text{LNA}} - 1) + \frac{T_{\text{PA}}}{I_{20}} \quad (2)$$

where F_{LNA} is the system noise figure from the LNA port onward, T_{PA} is the temperature corresponding with the noise power density at the output of the PA, and I_{20} is the isolation from the PA to the receiver in the 20-GHz band. In our FPA terminal for two-way satellite communication, the TX and RX antennas will physically share the same aperture. Therefore, the noise generated by the transmitter can strongly deteriorate the G/T ratio. As a consequence, a high TX–RX isolation is required. In order to quantify the required isolation, we characterized several commercially available 30-GHz PAs. The measured results are summarized in Table I. When we allow the G/T ratio to deteriorate 0.05 dB due to additional noise from the transmitter (corresponding to a noise temperature increase of 1.75 K), we need a worst-case isolation of $10 \log_{10}(1.75/22915) = 41$ dB. Next to additional receiver noise generated by the PA, we also need to take care of nonlinear effects in the LNA due to the strong 30-GHz signal. We will use the following assumptions.

- 1) The 1-dB compression point of silicon-based devices ($OP_{1\text{dB}}$) is in the range of +5 to +10 dBm.
- 2) The LNA has three stages with a total gain of about 15 dB ($G_{30\text{GHz}}$) for out-of-band signals.
- 3) In order to minimize the degradation of the RX noise figure, all input power levels should be 5 dB below the 1 dB compression point ($\Delta = 5\text{ dB}$).
- 4) Typical TX power for the PA, $P_{\text{out}} = 33\text{ dBm}$; see also Table I.

In order to keep the response of the LNA in the linear range, the following relation should be held:

$$P_{\text{out}} - I_{30 \text{ dB}} \leq OP_1 \text{ dB} - G_{30 \text{ GHz}} - \Delta \quad (3)$$

where $I_{30\text{ dB}}$ is the required out-of-band isolation at 30 GHz in decibels. Since the level of acceptable power ($OP_{1\text{ dB}} - G_{30\text{ GHz}} - \Delta$) at the input of the receiver is -15 dBm, one needs a minimum isolation of $I_{30\text{ dB}} = 48\text{ dB}$. Overall, we can conclude that we need (worst case) an isolation between TX and RX of 48 dB.

III. FILTERING SHARED APERTURE WITH DEFECTED GROUND STRUCTURE (DGS)

We propose an integrated shared-aperture concept, which integrates a dual-frequency antenna with a bandpass filter on a DGS into a single module, which can be made small enough to fit within a unit cell of an FPA. The radiating element, which we have used, is a dual-band aperture-coupled microstrip antenna (ACMA); see [9]. In [10] and [11], it was shown that these antennas demonstrate well-behaved radiation patterns in the low and high band and can be used to realize excellent

Fig. 1. Schematic concept and geometry of the shared aperture with embedded filter using a dual-band ACMA as the last stage of the N -stage coupled-line filter.

polarization properties with axial ratios below 1.2 dB. Fig. 1 shows the schematic diagram of the proposed coupled-line band-pass filter integrated with the antenna. Z_{0e} and Z_{0o} represent the even- and odd-mode line impedance of each section.

As a starting point in our filter design process, a Chebyshev bandpass four-stage filter is used. Note that other filter concepts can also be used. Next, the last stage of the filter is replaced by the equivalent circuit of the ACMA radiating element. One of the limitations in the design of the bandpass filter is the minimum line spacing allowed in the PCB technology, typically 70–100 μm . This limits the coupling that can be achieved between coupled lines. In order to improve the coupling, we will use a DGS. A DGS uses slots in the ground plane of a microstrip-based structure to enhance the coupling. Various DGS configurations have been proposed in the literature [12]–[14], mainly to achieve a larger rejection in the stopband. In this letter, we will use the DGS concept to realize a compact filtering shared aperture with a minimum line spacing of 100 μm . In the optimization of this structure using a finite-difference time-domain solver [15], we found that the coupling of two quarter-wavelength coupled microstrip lines with 100 μm spacing can be increased by approximately 2.5 dB as compared to a coupled-line structure without DGS. Fig. 2 shows the optimized layout of the shared aperture, where the coupled-line filter is realized in both the TX and RX channels. A prototype was built and experimentally verified. The measured and simulated performance is shown in Fig. 3. It can be noticed that the measured isolation at 30 GHz is about 35 dB. This is about 20 dB better as compared to a separate ACMA radiator. In Section IV, we will show that the TX filter can be omitted in case the shared aperture is combined with a filtering LNA. The observed measured peaks at 20 and 32 GHz in the isolation are most likely due to spurious radiation by the DGS slots. This can be improved by using a multilayer PCB technology with at least four metal layers. In this way, the coupled-line filters can be realized in stripline technology, and the corresponding DGS structures can be placed in the bottom ground layer of the stripline structure. As a result, the radiating antenna layer is isolated from the DGS structures. The overall size of the dual-band shared aperture can also be reduced by using such a multilayer PCB technology.

IV. HYBRID SOLUTION: ACTIVE SHARED APERTURE

As an optimal solution, we have combined an on-chip active filtering LNA with the dual-frequency shared-aperture

Fig. 2. Final layout of the dual-band filtering shared aperture using DGS. Dimensions: coupled-line spacing $s = 0.1$ mm, $\epsilon_r = 3$, $(h_1, h_2) = (0.254, 1.524)$ mm, $(L_p, W_p) = (2.85, 1.8)$ mm, $(S_{xl}, S_{yl}) = (3.2, 0.33)$ mm, $(S_{xh}, S_{yh}) = (0.25, 2.5)$ mm, $(L_{sl}, W_{sl}) = (2.55, 0.8)$ mm, $(L_{sh}, W_{sh}) = (1, 1.1)$ mm, $L_{sub,1} = 0.6$ mm, $L_{sub,h} = 0.2$ mm, $(L_{sl1}, W_{sl1}) = (1.63, 0.63)$ mm, $(L_{sl2}, W_{sl2}) = (1.5, 0.5)$ mm, $(L_{sh}, W_{sh}) = (1.68, 0.13)$ mm, $(W_{ml1}, W_{ml2}) = (0.6, 0.33)$ mm, $(W_{mh1}, W_{mh2}) = (0.45, 0.5)$ mm, $(L_{cl}, L_{ch}) = (2, 1.3)$ mm.

Fig. 3. (top) Measured input reflection S_{11} (RX port) and S_{22} (TX port) and (bottom) isolation of the filtering shared-aperture antenna.

antenna resulting in a highly integrated module. The filtering-LNA die is integrated in the backside of the antenna substrate using a wire-bonding technique. In order to meet the overall isolation requirement, a distributed filtering approach was chosen, in which part of the TX–RX isolation is realized in the LNA circuit with limited impact on the noise performance.

Although off-chip filters using low-loss materials can be used to solve the isolation problem in full-duplex systems, on-chip filters can be integrated with the rest of the front end with re-

Fig. 4. Photograph of the back side (top) and front (bottom) of the prototype. Four versions have been realized. Only the RX coupled-line filter is implemented in this prototype. Array spacing is 7 mm. Dimensions: see Fig. 2.

duced system size and cost. Typically, on-chip bandpass filters suffer from high insertion loss, which increases the noise figure of the system. This is especially the case if all the filtering is done at the input of the receiver, directly behind the antenna. Better noise performance can be achieved by implementing lumped-element notch filters at the input and in between the stages of the LNA. An advantage of this approach is the possible tradeoff between filtering and noise figure. We have developed a two-stage 20-GHz LNA realized in a $0.25\text{-}\mu\text{m}$ SiGe:C BiCMOS technology [8]. Between 27.5 and 31 GHz, the filtering LNA achieves an attenuation of more than 25 dB, with a worst-case degradation of the noise figure of 0.4 dB in the 18–22-GHz RX band (measured noise figure $F_{\text{LNA, dB}} = 1.95$ dB @ 20 GHz with filtering). In order to minimize the length and associated parasitic inductance of the bond wires, a cavity is made into the PCB in which the die is placed. The thickness of the die ($250\text{ }\mu\text{m}$) is almost the same as the substrate thickness ($254\text{ }\mu\text{m}$). The total structure of the antenna and bond-wire interconnections ($25\text{ }\mu\text{m}$ diameter) was optimized for a minimum reflection in the operational frequency band.

A 2×2 shared-aperture demonstrator was fabricated and experimentally validated. The primary aim of our 2×2 array prototype is to investigate the isolation within a single array element for several configurations of the on-chip and passive filtering structures. Fig. 4 shows a photograph of the backside of the realized 2×2 array with an indication of the different filtering combinations. Note that only

TABLE II
PERFORMANCE COMPARISON TO STATE-OF-THE-ART FILTERING SOLUTIONS

Ref.	Technology	Freq [GHz]	Isolation [dB]	Gain [dB]	Area [mm ²]
[19]	0.25 μ m pHEMT	11.5	35	-4.7	16
[2]	Gap waveguide	38	> 50	-	5.6
This letter	0.25 μ m BiCMOS+PCB	30	> 50	25	36 incl. dual-band antenna

Fig. 5. Measured TX-RX isolation of the active shared aperture (case 1 in Fig. 4) compared to an ACMA antenna with a nonfiltering LNA (case 4 in Fig. 4).

the RX filter is implemented in the shared aperture (compare to Fig. 2).

The measured coupling between the 30-GHz TX and 20-GHz RX port of a single array element is shown in Fig. 5. With the active shared aperture, an overall isolation of more than 50 dB can be realized at 30 GHz. This is about 30 dB better as compared to an ACMA element with a traditional nonfiltering LNA. The performance of our realized prototype matches very closely to the stringent isolation requirements of 48 dB for two-way satellite communications. With some further optimization, we expect that it will be possible to meet the requirement over the entire band. A comparison to other state-of-the-art solutions is presented in Table II. The shared aperture self-duplexing element concept was first introduced and used to construct dual-band circularly polarized self-duplexing arrays, employing the sequential-rotation technique [16], [17], see also Fig. 4. In this case, a small element spacing (< 0.5 wavelength for the higher band) is required to avoid high cross polarization lobes in the diagonal planes. The element can also be used to construct linearly polarized arrays or FPAs without this tight spacing requirement. When using this concept in large arrays, mutual coupling (e.g., blind scan angles) could deteriorate the isolation, particularly in case of circular polarization with small element spacing.

V. CONCLUSION

We have demonstrated an active shared aperture with embedded LNA concept that can meet the stringent TX-RX isolation, which is required in future FPA solutions for two-way satellite communications. In order to replace waveguide-based filtering in front of the LNA by integrated technology, the isolation re-

quirement of 48 dB can only be met by co-design of the antenna, filter, and LNA front end using a distributed filtering approach. The shared aperture uses the antenna resonator as one of the stages of a Chebyshev filter and applies DGS structures to realize a high coupling between the coupled lines having a minimum spacing of 100 μ m. The LNA includes notch filters at the input and inter stages.

Our concept limits the noise figure degradation to 0.4 dB for the worst case. A prototype antenna was developed with an embedded BiCMOS filtering LNA. The measured TX-RX isolation is better than 50 dB at 30 GHz. A future improvement can be realized by combining the electronics for multiple array elements into a single chip and by using a multilayer PCB technology, which allows the use of stripline technology. In this way, a more compact solution can be obtained, and spurious radiation from the DGS structure toward the FPA antenna can be reduced as well.

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