Decoupling Efficiency of a Wideband Vivaldi Focal Plane Array Feeding a Reflector Antenna

Marianna V. Ivashina, Malcolm Ng Mou Kehn, Member, IEEE, Per-Simon Kildal, Fellow, IEEE, and Rob Maaskant

Abstract—A focal plane array (FPA) feeding a reflector can be used to achieve a large field of view (FOV) with overlapping simultaneous beams. In order to provide a continuous FOV over more than an octave bandwidth, the inter-element spacing in the FPA has to be electrically small over large parts of the band. This will inevitably result in strong mutual coupling effects between the array elements. On transmit, the total lost power due to mutual coupling can be quantified by the decoupling efficiency, a term recently introduced for antenna arrays. This paper presents measured decoupling efficiencies of a Vivaldi element FPA operating between 2.3 and 7 GHz. The radiation patterns of the FPA are calculated for two beam excitations by using measured embedded element patterns, and the corresponding decoupling efficiencies are evaluated by using measured $S$-parameters between all element ports. The FPA is assumed to illuminate a deep reflector with $F/D = 0.35$, and the overall reflector aperture efficiencies are computed. The decoupling efficiencies are also determined through the measurements of the total radiation efficiencies in a reverberation chamber, which includes material absorption losses.

Index Terms—Antenna array feed, aperture efficiency, decoupling efficiency, mutual coupling, radiation efficiency, tapered slot antenna array.

I. INTRODUCTION

The field of view (FOV) of a reflector antenna can be increased by using multiple beams, e.g., by feeding it with a cluster of horns in a one-horn-per-beam configuration [1]. However, the size of such a FOV formed by horn clusters is limited due to aberrations and distortions of off-axis beams, causing a loss in aperture efficiency and thereby sensitivity. Although this can be improved by using reflectors with large focal ratios ($F/D > 1$) [2], as it is often done in deep space and satellite communication, this approach is not suitable for many radio telescopes, which have $F/D$ ratios that are typically smaller than 0.5. Hence, only a few radio telescopes have so far been equipped with cluster feeds [3].

Besides the size of the FOV, its continuity is also a vital parameter in radio telescopes, as this describes the ability to sample extended sources efficiently [4]. The decrease in gain at the crossover point of adjacent beams (or crossover loss) is commonly used to characterize the quality of the sampling. For reflectors with large $F/D$ (between 1 and 2), crossover losses were found within the $-6$ to $-15$ dB range, depending upon the type of horns in the cluster and their radiation patterns [5]. This extremely low crossover gain is a result of the undersampling of the focal plane fields due to the large spacing between the horns. For standard conical horns feeding reflectors with $F/D < 0.5$, the element spacing ($\sim \lambda$) is at least a factor 2 too large for realizing a $-3$-dB beam overlap, if a decent illumination of the reflector with low spillover is required [see [6, Fig. 1]], and, at least a factor 4 too large according to Nyquist’s sampling criterion to achieve a continuous FOV with a beam spacing of half of the half-power beamwidth (at least in theory) [7, 8]. This illumination of the reflector determines the aperture diameter of the horns and thereby the spacing. Therefore, such cluster feeds cannot be used to generate beams that produce a continuous FOV, corresponding to an overlap with $-3$-dB crossover losses as illustrated in Fig. 1 for two beams. Another problem with cluster-fed reflectors is that the quality of the beam varies with frequency.

All the aforementioned limitations may be solved by using a dense focal plane array (FPA) feed comprising many electrically...
small elements [9]–[12]. The overlapping beams are realized by grouping the FPA elements in overlapping subarrays that are excited independently and simultaneously. Thereby, each subarray can be optimized independently of one another to provide high aperture efficiency of their specific beams (even off-axis ones), as well as to obtain a more continuous FOV. A good initial starting point for optimizing the excitation of such a beam-specific subarray is to match the excitations to the conjugate of the focal field of the reflector (corresponding to that beam) at the location of the center of each element in the subarray [13], [14]. The schematic of such a system is illustrated in Fig. 1. Two overlapping focal plane fields can be seen, corresponding to closely separated beams. Any FPA element located within the overlapping field regions on the focal plane contributes to all those overlapping beams concerned. Moreover, the excitations of the subarray elements can be allowed to vary with frequency, thereby mitigating the previously mentioned beam variation with frequency. This enables FPA feeds to efficiently illuminate the reflector over a large 4 : 1 bandwidth [15], depending upon the type of element and the size of the array.

It is postulated that, in order to provide a continuous FOV over more than an octave bandwidth, the inter-element spacing in the FPA needs to be in practice smaller than 0.5λ over the entire band. However, this in turn will result in strong mutual coupling and associated mismatch losses at the element ports. These losses cannot be corrected for by conventional “active” impedance matching techniques that are used for classical beam-steered arrays with strongly coupled elements. In fact, all elements of the FPA will have very different weights (including zero weights) when they are used for sampling the focal plane fields, and because each element may contribute simultaneously to several beams, their excitation environment is nonunique. In [16], it is proposed to characterize this loss in terms of a decoupling efficiency $\eta_{\text{decouple}}$, which will be different for different excitations, i.e., beams (see Fig. 2).

The decoupling efficiency is defined as the ratio of the array’s accepted power $P_{\text{acc}}$ to the incident power $P_{\text{inc}}$. Note that, under dissipationless conditions in which ideal lossless materials are involved (i.e., $\varepsilon_{\text{rad}} = 1$), $\eta_{\text{decouple}}$ will be given by $\eta_{\text{decouple}} = P_{\text{rad}}/P_{\text{inc}}$, where $P_{\text{rad}}$ is the total radiated power. The product of $\eta_{\text{decouple}}$ and $\eta_{\text{rad}}$ constitutes the total radiation efficiency $\eta_{\text{totrad}}$, which is a quantity that can be directly measured in a reverberation chamber (see Section IV and [17] and [18]).

The objective of this paper is to determine the decoupling efficiency of a dense FPA of Vivaldi elements, which was designed for the Westerbrook Synthesis Radio Telescope (WSRT) [19]. The results have been obtained experimentally through measurements of embedded element patterns as well as the $S$-parameters between the ports of all the array elements.

II. DESCRIPTION OF THE VIVALDI ELEMENT ARRAY

The considered FPA is a dual-polarized array of 144 Vivaldi antenna elements, consisting of $2 \times 72$ linearly polarized elements arranged in an $8 \times 9$ grid [15], as shown on the right side of Fig. 3. Each element represents a bilateral tapered slot antenna (TSA) that is excited by a wideband stripline feed (left side of Fig. 3) embedded in a homogeneous dielectric ($\varepsilon_r = 3.5$). Vias have been placed along the contours of the Vivaldi element and feedline to prevent undesired parallel plate modes and associated impedance resonances from occurring [20].

The Vivaldi array that has been used was initially designed by means of an infinite array approach, since it was aimed to be used in phased-array applications [15]. More recently, however, full-wave numerical modeling techniques have been considered to accurately design and analyze large arrays of arbitrary excited elements [21].

The next sections contain results for this FPA over the frequency band ranging from 2.3 to 7 GHz, inside which the element spacing changes from 0.2λ to 0.63λ.

III. A FPA SYNTHESIS USING THE $8 \times 9 \times 2$ VIVALDI ANTENNA ELEMENT ARRAY

A. The Conjugate Field Matching Method

The elements of the FPA are grouped into subarrays and excited with unique sets of complex coefficients. The configuration and excitations of the subarrays are herein determined using the conjugate field matching (CFM) method [22], [23]. For this purpose, the reflector was illuminated by an incident plane wave and the focal field distribution of the scattered field from the reflector was computed by means of the physical optics/physical theory of diffraction (PO/PTD) technique in General Reflector Antenna Software Package (GRASP9) [27]. Next, the excitations of the elements of the subarrays were conjugately matched to this computed focal field. We point out that the CFM used here basically adopted a point matching approach, as each Vivaldi element is excited according to the conjugate value of the aperture field distribution at its center, and is equivalent to

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1 In previous conference papers, we termed this efficiency a “coupling efficiency,” whereas we currently prefer to use the more correct and descriptive term “decoupling efficiency,” because it describes how decoupled each beam excitation is from other port excitations.
treatment of the array elements as point sources. Obviously, a more accurate way to perform the CFM in the process of determining an element weight/excitation is to conjugately match the focal field distribution over the entire physical aperture area of that element, e.g., in an average best manner. Nonetheless, the point matching method turned out to be simple, though sufficiently accurate, and thus serves here as a convenient approximation.

Note that the CFM is repeated for the focal plane fields of each desired beam and the corresponding subarrays. Hence, each achievable beam direction from the reflector pertains to a certain subarray and to certain amplitude and phase excitations of the subarray elements. In this paper, numerical results are presented only for axial beams, whereas the analysis of the off-axis beams is left for future studies.

For practical antenna systems, CFM can be realized only over a fraction of the focal field distribution. In general, and provided that there is an adequate number of sufficiently dense subarray elements, the more sidelobes (rings) are excited by the subarrays, the better will the illumination of the reflector be and thereby the higher aperture efficiency is achieved (when aperture blockage and mutual coupling are neglected) [23], [24]. In addition to this truncation, the focal plane field is discretized due to the finite number and finite size of elements in the feed. The consequence of this truncation and discretization is a reduced aperture efficiency of the reflector.

A further reduction in the aperture efficiency manifests itself when a practical array is not capable to provide the conjugate field match to the greatest degree. This may, in particular, be the case in deep reflectors where field contributions reflected from near the reflector edge arrive along almost horizontal ray paths, and therefore, cannot be reconstructed by a planar horizontally oriented FPA.

Another limitation with the CFM approach is that it generally does not lead to the optimum sensitivity of the antenna system. Furthermore, the FPA structure itself is not included when evaluating the focal field. Therefore, the final optimization was done with the aid of a transmit mode analysis, by using the truncated and discretized computed focal field as an initial choice for the excitation of the subarray, and performing further optimizations by computing the radiation pattern of the FPA from the excitations and measured embedded element patterns as will be described in Section III-C.

B. Mapping of the Focal Field on the Subarrays

The focal field distribution is truncated to retain the main beam of the Airy-like distribution along with the first two sidelobes at the highest operational frequency, whereas only the main beam is retained at the lowest operational frequency. The elements that are not excited are match-terminated as defined in [16].

The diagrams in Fig. 4(a)–(c) illustrate the 8×9×2 Vivaldi element array and the respective FPA subarray elements that were used to synthesize the focal field, as well as a generic beamformer topology [Fig. 4(d)]. The beamformer ensures that the elements are excited with the complex coefficients according to the CFM method. Only the ypolarized Vivaldi elements were used in the beamforming for generating the focal plane fields that correspond to a linearly ypolarized axially incident plane wave on receive. Note that, at different frequencies, the FPA subarrays are realized with a different number of active elements, but for all cases with an odd number of elements along both the x- and y-directions. The central element coincides with the focal point of the paraboloid. In this study, the outer array elements are not included in the beamforming as their patterns are highly asymmetrical and their reflection coefficients are high (> -8 dB). Therefore, the largest excited subarray is composed of 5×5 elements. All nonexcited cross- and copolarized (dummy) elements are match-terminated to the characteristic impedance of the stripline feed. At low frequencies (2.3–3 GHz), the 25 active subarray elements are arranged as shown in Fig. 4(a), and excited such as to approach a conjugate match to the mainlobe of the computed focal plane field [see Fig. 5(a)]. At 3.5 GHz, this mainlobe is narrower so that the 25 elements are also capable of reconstructing the first sidelobe of the focal plane field [see Fig. 5(b)]. For higher frequencies, even fewer elements can be used [see Fig. 5(c) and (d)], i.e., 21 elements at 4–4.5 GHz for creating the mainlobe and first sidelobe, and 13 elements at 5–7 GHz to reconstruct the mainlobe and first two sidelobes.

C. Optimization

We point out that the CFM does not provide the optimum sensitivity (Aeff/T50%) of the antenna, because the uniform illumination of the reflector may lead to more spillover and, consequently, a reduced aperture efficiency as well as a higher total
was computed as a product of the number of subarray elements (size and the decoupling efficiency). The latter was assumed to be determined and have zero amplitude coefficients. (a) Element separation 0.25; (b) element separation 0.32 λ; (c) element separation 0.4 λ; and (d) element separation 0.5 λ.

After determining an initial set of element excitations via CFM (see Section III-B), the FPA illumination pattern was computed by superposing embedded element patterns of a subarray. From the illumination pattern, the aperture efficiency and spillover noise temperature were calculated using the expressions in [25]. Also, the decoupling efficiency and spillover noise temperature were calculated using subarray. From the illumination pattern, the aperture efficiency for achieving high taper efficiency of the conventional aperture efficiency the total aperture efficiency the contributions: the spillover temperature and a theoretical system noise temperature due to pickup of ground noise. Therefore, a refinement of the excitation scheme is needed as described next.

After determining an initial set of element excitations via CFM, the FPA illumination pattern was computed by superposing embedded element patterns of a subarray. From the illumination pattern, the aperture efficiency and spillover noise temperature were calculated using the expressions in [25]. Also, the decoupling efficiency was evaluated for these initial excitations through the measured S-parameters between all element ports (Fig. 2). Afterwards, the total aperture efficiency was computed as a product of the conventional aperture efficiency and the decoupling efficiency (see Section I, and the definition of εdecoup in [16] under dissipationless conditions when εrad = 1). When ignoring the receiver gain, the effective area Aeff at the beamport (output defined in Fig. 2) is computed as

\[
A_{\text{eff}} = A_P \varepsilon_{\text{ap}} \varepsilon_{\text{decoup}}
\]

where \(A_P\) is the physical area of the reflector. Herein, one observes that, besides the traditional tradeoff between the spillover and illumination taper efficiency for achieving high \(\varepsilon_{\text{ap}}\), one also has to account for the array’s decoupling efficiency. Therefore, one also has to minimize for the mismatch losses at actively used elements and the absorption losses in dummy loads (Fig. 4(d)) for achieving overall best \(A_{\text{eff}}\) (note that \(A_{\text{eff}}\) is referred to the beamport).

In addition to \(A_{\text{eff}}\), the system noise temperature \(T_{\text{sys}}\) was determined for the initial set of excitations as a sum of two main contributions: the spillover temperature \(T_{\text{sp}}\) that was directly computed from the feed pattern of the subarray [25], and the total receiver noise temperature \(T_{\text{REC}}\). The latter was assumed to be a priori known, constant, and estimated to be around 150 K (at the beamport). This noise temperature primarily includes the measured uncooled amplifier noise temperature of 120 K, the increase in noise temperature due to undesired noise coupling effects of dummy loads [Fig. 4(d)] and amplifiers, and the second stage noise contribution (vector modulators). Thus, the excitation-dependent noise coupling effects have not been treated within the scope of this paper and are left to be studied in future. In fact, it is currently believed that the decoupling efficiency can be used to determine the noise coupling between the receivers on the different ports and its contribution to the system noise temperature, but this still remains to be proven.

Note that the FPA system that has been exemplified in this paper is receiver-noise dominated, since the spillover noise temperature is typically in the order of tens of Kelvins. As a consequence, we basically optimize to achieve overall best \(A_{\text{eff}}\) in (1).

After computing the receiver sensitivity for the initial set of excitations, an iterative optimization procedure was employed, which is based on a simplex search method, to tune the excitations such as to achieve optimum receiver sensitivity [26].

D. Beamformer Realization and Characterization

Fig. 6(a) depicts the realized subarray configuration and beamformer topology of an FPA that is excited at 5 GHz (element spacing is 0.45 λ). The number of subarray elements (size of the subarray) has been determined by means of the CFM method (Section III). A multistage active beamformer was manufactured to equally weight the elements that are located within each of the squarish-shaped rings of the subarray. The first stage of the beamforming network reduces the degrees of freedom of the weights from 13 to 4 [see Fig. 6(b)]. This significantly eases the beamformer realization and FPA optimization, though it may lead to a nonsymmetrical (squarish) beam pattern and, consequently, a slightly reduced illumination taper efficiency of the reflector [as will be shown in Fig. 10(b)].

Next, the second stage of the beamforming network, composed of the three vector modulators (weights) and the four-port power combiner, was calibrated such that the actual realized weights were equal to the specified weights. Afterwards, the
$S$-parameters between the external ports of the cascaded multistage beamformer were measured under match-terminated conditions, and the weights were adjusted such as to provide an almost equal set of transmission coefficients for the 13 beamformer channels. The purpose of the latter weight adjustment was to calibrate for the first stage of the beamforming network.

As a result of this calibration, the relative amplitude and phase differences of the transmission coefficients between four measured beamformer channels that are associated with the same ring were found to be smaller than 0.12 dB and $5^\circ$. This difference was found to be slightly larger between beamformer channels that do not belong to the same ring and is primarily caused by the finite amplitude and phase step resolution of the vector modulators.

Finally, the 13 embedded element patterns were measured and superimposed for a certain set of weights, and then compared to the total FPA subarray pattern, which was measured with the beamformer realizing the same weights. The shapes of the patterns were in excellent agreement, demonstrating that the differences between channels of the practical beamformer were accurately calibrated out.

The realized excitation coefficients of the practical FPA are listed in Table I (5 GHz) and visualized in Fig. 7. These coefficients were both determined through the CFM method, however, in one case, the weights were further optimized so as to reach optimum sensitivity (Section III-C). Clearly, the optimized weights for the first and third rings (elements #2-5 and #10-13, respectively) differ greatly with respect to those obtained through the CFM procedure. To explain this, we recall that the CFM method is primarily useful for determining the size and element configuration of the subarray, as well as to determine the initial set of weights for ideally point-matched array elements, whereas a weight optimization is required for a practical array of strongly coupled array elements. Furthermore, the CFM weights are aimed to provide the maximum illumination taper efficiency of the reflector aperture (i.e., a uniform amplitude-phase illumination), whereas the proposed optimization procedure maximizes the sensitivity, though for the present system it effectively searches for the maximum total aperture efficiency.

Not surprisingly, the optimized weights are, therefore, very different, since a tradeoff is found between the maximum illumination taper efficiency of the FPA-fed reflector and a minimum spillover and power loss due to impedance mismatch and (dummy) load absorption effects in the array.

### IV. RESULTS AND DISCUSSION

It will be demonstrated that the decoupling efficiency has a considerable effect on the total aperture efficiency. For this purpose, the decoupling efficiency of the Vivaldi FPA is evaluated for various sets of excitations between 2.3 and 7 GHz (element spacing ranged from $0.2\lambda$ to $0.63\lambda$).

The $S$-parameter matrix was measured in order to compute the decoupling efficiency (see Fig. 2). The matrix was measured fully for the 25 elements in the core of the array [see Fig. 4(a)], after which we proceeded to only measure couplings between element pairs that have a unique separation distance and mutual orientation and, henceforth, symmetry was used for the remaining elements to construct the entire $144 \times 144$ scattering matrix. Obviously, not only the relative position between elements is of importance, but also the absolute position with respect to the edge of the array. The validity of these symmetry assumptions is, therefore, rather good at high frequencies but degrades at lower frequencies as the array is then electrically small so that the asymmetry is more pronounced.

For pedagogical purposes, the decoupling efficiencies were evaluated also for an embedded element and when all elements were excited with equal weights to create a pencil beam in broadside direction.

#### A. Decoupling Efficiency for the Embedded Element and All-Excited Array Scenarios

Fig. 8 shows the calculated decoupling efficiency of the singly excited embedded element and its contributions from reflection on the excited port and dissipations in the loads on the nonexcited ports. The embedded element efficiency decreases rapidly as the element separation becomes electrically small. This is expected and in accordance with the theoretical slope calculated using the approximate formula in [16, eq. (5)].

Another operational scenario is the all-excited phase-steered array shown in Fig. 9 (broadside scan). Herein, all antenna elements are “actively” used for beamforming so that, as explained in [16], the decoupling efficiency reduces to a mismatch efficiency. This mismatch efficiency varies very little with element spacing, which means that the elements are well matched over the frequency band.
B. Decoupling Efficiency of the FPA With Individually Weighted Subarray Elements [Fig. 4(d)]

The decoupling efficiencies of the three different subarrays shown in Fig. 4(a)–4(c) were analyzed at ten frequencies in the range of 2.3–7 GHz (element spacing ranges from 0.2λ to 0.63λ). In this example, the CFM approach is employed without optimization, and weights are assigned to individual array elements. The decoupling efficiencies of the respective FPA subarrays are shown in Fig. 9 together with the results for the embedded element and the all-excited broadside-scanned array case.

It has been observed in [16] that the decoupling efficiency of the FPA is typically bounded between the decoupling efficiencies of the embedded element and the all-excited array. This can also be seen in Fig. 9 for the Vivaldi array. For the FPA case with element spacings larger than 0.3λ, it is concluded that the decoupling efficiencies are quite high (> −1.3 dB), whereas for smaller inter-element spacings (lower frequencies) the decoupling efficiency drops down to −3 dB when the element separation approaches 0.2λ.

C. Decoupling and Aperture Efficiency of the Practical Beamformed FPA With Weighted Rings of Elements (Fig. 6)

Results are presented on both the decoupling efficiency of the practically realized FPA system, and the resultant aperture efficiency of the reflector (F/D = 0.35). The aperture efficiency εap was calculated from the total measured FPA subarray pattern that was realized with the beamformer of Fig. 6. Two sets of excitation coefficients were considered: a set determined by the CFM approach and an optimized weighting scheme for achieving the maximum sensitivity (in effect, the maximum total aperture efficiency).

Each FPA subarray pattern was measured at 5 GHz in an anechoic chamber equipped with a planar near-field scanner. The respective patterns are shown in Fig. 10, both for the CFM approach [Fig. 10(a)] and the optimized excitation case [Fig. 10(b)]. On account of the CFM excitation in Fig. 7(a), the subarray pattern should almost resemble the embedded element pattern of the central element since the excitations of the surrounding elements are strongly attenuated; hence, it is therefore characterized by a rather broad beamwidth and realizes an almost uniform illumination of the reflector.

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a result, the FPA-fed reflector suffers from significant edge illumination, and consequently, large spillover.

The pattern in Fig. 10(b) represents a modified secant-squared pattern with a sharp cutoff toward the rims of the reflector ($\theta \approx 70^\circ$). This pattern has a squarish shape, which can be partly attributed to the corresponding rectangular configuration of the subarray and identical excitation of the elements within the same rings (see Table II), as mentioned earlier. Besides, this illumination pattern may be intrinsic to a square-grid array with spacing in the order of $0.5\lambda$, which may be too large for the short $F/D$ ratio as considered in our example. Finally, we remark that the patterns are accurate only up to $75^\circ$ due to the limited scan range of the near-field probe.

Based on the measured S-parameters and patterns at 5 GHz, several contributions to the total aperture efficiency of the FPA-fed reflector were calculated and presented in Table II. For this ring-excited FPA case, the decoupling efficiency for the CFM ring weights was found to be $-1.1$ dB, but improved significantly to $-0.5$ dB after applying the optimized excitation coefficients for these subarray rings. Also note that, when subarray elements can be individually weighted (Section IV-B), the corresponding decoupling efficiency for the CFM element weighted case is already $-0.75$ dB (see Fig. 9). Although not analyzed, a further increase in the decoupling efficiency is expected when all individual element weights are optimized.

Reverting to the ring-excited FPA (Table II), the illumination taper efficiency for the CFM excited case is relatively high and equal to $-0.74$ dB. This high efficiency is primarily attributed to the broad (embedded) element pattern of the central element as the surrounding elements of the subarray are strongly attenuated [see Fig. 7(a)]. However, the noise temperature due to the 10% spillover loss is rather high, i.e., $T_{sp}$ = 30 K. On the other hand, the optimized ring-excited FPA [Fig. 7(b)] demonstrates a decreased illumination taper efficiency of $-1.82$ dB, whereas the spillover temperature $T_{sp}$ has much improved ($T_{sp} = 3$ K).

The total aperture efficiency in Table II is 53% for the optimized subarray excitation, which is slightly higher than 48% for the CFM excitation. Likewise, the sensitivity of the optimized subarray excitation is higher than that of the CFM-excited FPA, because $T_{sp}$ has improved as well.

### D. Measurements of the Total Radiation Efficiencies in a Reverberation Chamber

The decoupling efficiencies of both the embedded element and FPA-excited cases were calculated and compared to those measured in a reverberation chamber. It is important to note that the measured efficiencies are the total radiation efficiencies $\varepsilon_{\text{tot rad}}$, defined as

$$\varepsilon_{\text{tot rad}} = \frac{P_{\text{rad}}}{P_{\text{inc}}} = \varepsilon_{\text{rad}} \varepsilon_{\text{decoup}}$$

and thus also include possible ohmic losses quantified by $\varepsilon_{\text{rad}}$. Hence, the currently computed decoupling efficiencies can only be compared to these measured efficiencies by imposing the condition that $\varepsilon_{\text{rad}} = 1$, which may be rather approximate as it also depends upon the array excitation.

The measurements were performed with accuracies that were typically better than 0.5-dB root mean square (RMS) in the 2–6-GHz range in the Bluestest (Gothenburg, Sweden) high-performance reverberation chamber. The details on the measurement accuracy are described in [17], whereas the measurement approach itself for both single- and multiport antennas is described in [18].

1) The Embedded Element Efficiency: Fig. 11 shows the resemblance between the measured decoupling efficiency of the embedded element and the sem calc ulated one that was evaluated through measured S-parameters. The agreement is very good at frequencies above 4 GHz (element spacing $d > 0.35\lambda$) and slightly worse at lower frequencies, where the maximum discrepancy is about 2 dB. The measured curve is closer to the values predicted by the approximate formula for the embedded element efficiency of an infinite array of electrically small apertures [16, eq. (5)].

The discrepancy between the measured and calculated curves is partly attributed to the ohmic losses in the materials of the Vivaldi array. The ohmic losses are included in the previously measured S-parameters, thus making the measured S-parameters look lower than those measured in the absence of absorption effects. Consequently, the calculated decoupling efficiency will be higher since the respective array’s absorption losses are accounted for in the radiation efficiency, which has not been deter-

### Table II

<table>
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<th>Several efficiency contributions</th>
<th>CFM</th>
<th>CFM with optimization</th>
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<td>Total aperture efficiency, $e_{tot}$</td>
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determined in this study. Another cause for the discrepancy in Fig. 11 is that part of the measured S-parameter matrix was constructed by exploiting symmetry under the assumption that the edge effects are small (see the opening sentences of Section IV). This approximation may affect the accuracy of the S-parameters, particularly at low frequencies.

The measured total radiation efficiency of the embedded element suffers from 1-dB oscillations at frequencies between 4 and 6 GHz. We believe that this is attributed to the two calibrations that were separately carried out for the lower (2–4 GHz) and upper (4–6 GHz) part of the band. There may also be a problem with phase stability of the cables and switches following the reverberation chamber in the higher frequency band, affecting the quality of the calibration of the measurement setup.

2) The FPA Decoupling Efficiency: In order to measure the decoupling efficiency of the FPA inside a reverberation chamber, and in an accurate and direct manner, it is desired to use a passive combiner/splitter network for realizing the element weights at each discrete frequency. Two FPA-excited cases have been considered: a subarray excited at 2.3 GHz and in an accurate and direct manner, it is desired the decoupling efficiency of the FPA inside a reverberation chamber, and this is generally smaller than the power that is incident to the input port of the power splitting (beamforming) network. As a result, the measured total radiation efficiency in (2) does not only include ohmic material losses of the antenna, but also relatively large beamformer absorption losses. The total beamformer absorption losses can be separately measured under match-terminated conditions and, subsequently, be used as a correction to obtain the total radiation efficiency $\varepsilon_{\text{tot,rad}}$ of the array only.

Fig. 12(a) and (b) illustrates the measured total radiation efficiencies for the FPA-excited case at around 2.3 and 5 GHz, respectively, both before and after correcting for the beamformer absorption losses. Upon inspecting the power splitting topology in Fig. 12(a), it is readily seen that one fourth of the input power to this splitter will be dissipated in the pertaining load, implying that the total attenuation under matched-terminated conditions is at least 1.2 dB. In fact, the total measured attenuation turned out to be $\approx$2 dB due to additional transmission-line losses. This loss has been subtracted (in decibels) from the measured total radiation efficiency so as to obtain the total radiation efficiency of the FPA only [see Fig. 12(a)]. In a similar manner, the total radiation efficiencies in Fig. 12(b) have been corrected. In that case, two passive beamformers have been constructed to realize both the CFM and optimized weight excited cases at 5 GHz. Furthermore, since the complexity of the beamformer at 5 GHz is larger (13 weighted elements), the respective absorption losses are larger than those measured at 2.3 GHz.

<table>
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<th>Method</th>
<th>Elements #2-5</th>
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</table>

2.3 GHz

Fig. 12. Measured radiation efficiencies of the FPA subarrays, both with and without correcting for the passive beamformer losses, measured in the reverberation chamber at around (a) 2.3 GHz and (b) 5.0 GHz. For the 2.3-GHz case, the element weights are visualized in the upper left-hand side of the graph, and the topology of the beamformer in the upper right-hand side. The radiation efficiencies after removing the beamformer losses are decoupling efficiencies.
The measured FPA total radiation efficiencies from Fig. 12 (after correction) have been compared to the calculated ones that have been evaluated via measured $S$-parameters (assuming $\varepsilon_{\text{rad}} = 1$, and weights according to Table III). The results are shown in Table IV for comparison.

A good agreement is observed between the measured and calculated results. However, it is remarkable to observe that the agreement between the measured and calculated efficiencies at 2.3 GHz is better for the FPA-excited case than for the embedded element scenario where the difference is almost 2 dB (Fig. 11). To some degree, this could be caused by the fact that the radiation efficiency of the antenna is also dependent upon the array excitation, and therefore, it may be that $\varepsilon_{\text{rad}} \ll 1$ for the embedded element scenario, whereas it is close to unity for the FPA-excited case, although this is difficult to confirm in practice.

V. CONCLUSION AND FUTURE STUDIES

This work has investigated the characteristics of a dense Vivaldi FPA that operates over a wide frequency range from 2.3 to 7 GHz, feeding a deep reflector antenna with $F/D$ ratio of 0.35 (subtended half angle 70°). The mutual coupling between the FPA elements is strong and is shown to limit the usable frequency bandwidth for maintaining a high total aperture efficiency. Particularly at low frequencies, the total aperture efficiency may be reduced strongly due to power absorption losses in the antenna terminations on both excited and nonexcited ports. The pertaining total power loss is herein quantified by a decoupling efficiency, and the total aperture efficiency is defined as the product of the conventional aperture efficiency and the decoupling efficiency.

The decoupling efficiency has been evaluated for FPA excitations determined from the CFM method. Efficiencies between $-0.5$ and $-1.1$ dB are reached over a large frequency band ranging from 3.4 to 7 GHz, corresponding to element spacings $d$ between 0.3$\lambda$ and 0.6$\lambda$.

It has been demonstrated for an example that the total aperture efficiency of a dense FPA can be improved by optimizing the excitation coefficients. Further optimizations may yield higher efficiencies, e.g., by using more active elements at the lowest frequencies to also sample the first and second sidelobes of the Airy pattern. In fact, it is important to have numerical and experimental control over the decoupling efficiency so as to ensure optimum performance of an FPA. For instance, the decoupling efficiency can be improved by increasing the $F/D$ ratio of the reflector thereby enabling us to employ FPAs of antennas with larger separation distances so as to reduce the coupling between array elements. This, however, will be a tradeoff with the total achievable bandwidth.

We point out that the decoupling efficiency reduces to the embedded element efficiency for a singly excited element, and the impedance mismatch factor for the all-excited phase-steered array [16]. Hence, the decoupling efficiency represents a unifying parameter as it quantifies the loss due to mutually coupled power for any array excitation.

A method has been described to measure the total radiation efficiency of an FPA system in a reverberation chamber. The measured total radiation efficiencies of the considered subarray examples are in good agreement with the calculated decoupling efficiencies (using measured $S$-parameters), when the radiation efficiency may be assumed unity. However, this discrepancy may be larger, since the radiation efficiency not only depends on the antenna materials that are involved, but also on the type of array excitation.

In future studies, it is to be demonstrated how the decoupling efficiency affects the receiver sensitivity of FPA systems. It will be vitally important to look into the role of the decoupling efficiency on the total system noise temperature for (actively) beamformed arrays of mutually coupled elements causing strong noise coupling effects.

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REFERENCES


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