

Near-Field Focused Microwave Antennas

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Abstract—Focusing the electromagnetic field radiated by an antenna at a point in the antenna near-field region is a well-known technique to increase the electromagnetic power density in a size-limited spot region close to the antenna aperture. The present survey encompasses the basic working principles and the applications of the near-field focused microwave antennas, as well as the synthesis procedures suggested for the near-field shaping around the focal point and the technologies currently used for their implementation.

Index Terms—Near-field focusing, near-field focused antennas, near-field shaping, microwave focusing

I. INTRODUCTION

NEAR-FIELD Focused (NFF) antennas cannot be identified as a new class of antennas, as they are well-known since a long time [1]–[18]. Nonetheless, research activities in NFF microwave antennas proliferated significantly over the last two decades. This survey encompasses the basic working principles and applications of the NFF microwave antennas, as well as the synthesis procedures suggested for the near-field (NF) shaping around the focal point and the relevant implementation techniques. The analysis is concentrated on NFF antennas with the focal point located in the antenna radiative NF region.

II. MAIN FEATURES AND BASIC METRICS

Focusing the electromagnetic field at a point in the antenna NF region allows to increase the electromagnetic power density in a size-limited spot region close to the antenna aperture. The basic idea (coming from optics) is to control the phase of the radiation sources on the antenna aperture (array element currents or equivalent surface currents) in such a way that their field contributions sum constructively at the assigned focal point. Specifically, by applying a ray-optics approximation it comes out that the source phase profile has to compensate for the phase delay introduced by the path between each source point on the antenna/array aperture and the targeted focal point, so generating spherical equi-phase surfaces converging at the focal point (Fig. 1).

As an example, Fig. 2 shows the normalized power density radiated by a 2.4 GHz planar array of circularly polarized (CP) patches [41] along the boresight direction, for both an 8×8 NFF array and the corresponding conventional 8×8 FF-focused array where all patches are fed in phase. Both arrays are fed with the same input power, and a uniform amplitude excitation is considered. The interelement spacing is $d = 0.8\lambda$ and the array size is $L = 6.4\lambda$ (λ is the free-space wavelength). For the NFF array, the assigned focal distance is $R_F = 8.2\lambda \sim 1$ m, and the focal distance normalized to the FF-region boundary, namely $\gamma = R_F / (2L^2/\lambda)$ [10], [42], is equal to 0.1.

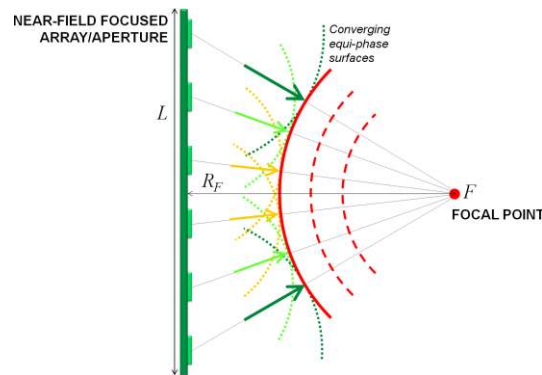


Fig. 1. Converging equi-phase surfaces of the field radiated by electromagnetic sources that are located on a planar aperture and focused at a focal point, F , in the antenna radiative near-field region. L and R_F denote the antenna aperture size and the focal distance, respectively.

It is apparent that the NFF array is able to increase the field amplitude in the antenna NF region, while also reducing the far-field radiation with respect to the corresponding FF-focused array. For the case here analyzed it follows that, for an assigned

maximum amplitude of the radiated field in the antenna far-field (FF) region, the power density radiated by the NFF antenna around the focal point is almost 20dB larger than that one radiated by the corresponding unfocused array in its NF region [42]. Otherwise, the NFF array can be used to achieve the required power density in a spot region around the focal point with a minimal radiation in the FF-region where the focusing effect is lost (around 20dB less with respect to the unfocused array). In Fig. 2, the focal shift and the focusing gain are also shown. The focal shift is the distance between the assigned focal point and the actual location of the field amplitude peak [42]. The focusing gain [10], [42], is defined as the ratio between the peak power density of the NFF array and the power density radiated by the corresponding unfocused array at a distance $2L^2/\lambda$ from the array aperture in the antenna boresight direction. Another important feature of the NFF antennas is the size of the 3D region around the focal point where the radiated power density normalized with respect to its maximum value is greater than -3 dB. Indeed, the above size is the main requirement when NFF antennas are used to increase the spatial resolution in imaging or inspection systems. If the focal point lies on the antenna boresight direction, the depth of focus, DoF , is defined as the range between the -3 dB axial points around the point of maximum power density, along the direction normal to the antenna aperture (Fig. 2). Also, the focus width, W , is defined as the -3 dB spot diameter in the focal plane parallel to the antenna aperture. In multi-focus and focus-scanned NFF antennas, it can happen that the focal point is located out of the direction perpendicular to the array/antenna aperture. In this case, the size of the -3dB focal spot can be rationally quantified by using the DoF measured along the direction going from the antenna center to the focal point, and the focus width W measured at the focal plane orthogonal to the above direction.

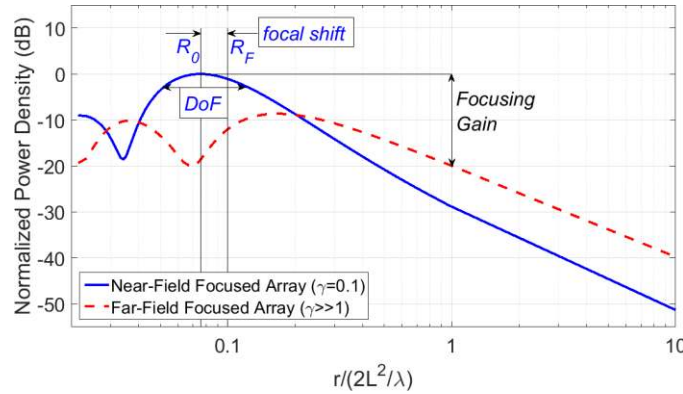


Fig. 2. The normalized power density radiated by an 8×8 array of 2.4 GHz microstrip CP patches, along the direction perpendicular to the array surface (on-axis power density): a NFF array (solid line) and the corresponding conventional 8×8 FF-focused array (dashed line). Both arrays are fed with the same input power level. The distance from the array surface (r) is normalized to the far-field region boundary ($2L^2/\lambda$). For the NFF array, the focal distance is $R_F = 8.2\lambda \sim 1$ m ($\gamma = R_F/(2L^2/\lambda) = 0.1$).

NFF antenna parameters mainly depend on the antenna electrical size, L/λ , and the focal distance normalized to the antenna size, R_F/L . In [42], Buffi *et al.* summarized the basic design criteria for NFF planar square arrays. There, a set of numerical results are shown to underline that, for a given NFF antenna focused along the boresight direction, both the DoF and the focus width increase when the focal point moves far from the array plane. Also, for a given focal distance, focusing performance improves for larger antennas. Above numerical results agree with approximate expressions derived for the -3 dB focus width, W , which have been originally presented for electrically large NFF squared apertures with a uniform amplitude excitation [3], [5]: $W \sim R_F(\lambda/L)$. For a given NFF antenna, focusing performance gets worse if the focal point moves out of the antenna axis.

Since electrically large arrays/apertures are needed to increase the performance of NFF antennas, it is apparent that, at the microwave frequency band, the main limit to the adoption of NFF antennas is the maximum extent allowed for the antenna into the operating area. It follows that the antenna size is usually less than a few tens of wavelengths, and then the DoF is always larger than the focus width [57].

A further parameter used to characterize NFF antennas is the level of the secondary lobes around the focal spot region, namely the axial lobes (forelobes and aftlobes) and the sidelobes [3], [9], [42]. If the focal point is located out of the antenna boresight direction, axial lobes and sidelobes can be measured along the direction going from the antenna center to the focal point and at the focal plane orthogonal to above direction, respectively. As an example, the normalized power density in the focal plane is shown in Fig. 3 for the same NFF array as that in Fig. 2. The focus width is $W = 14.7$ cm, while from Fig. 2 it results that $DoF = 71$ cm. The sidelobe level in the focal plane is less than -15 dB.

Typical parameters of conventional FF-focused antennas (radiation pattern, antenna gain) are also of interest in most of the NF applications, to quantify the capability of the NFF antenna to minimize the field radiated in the FF-region. For the highly directive 8×8 FF-focused array the gain is 20.6 dB, while it goes down to 9.2 dB for the 8×8 NFF array.

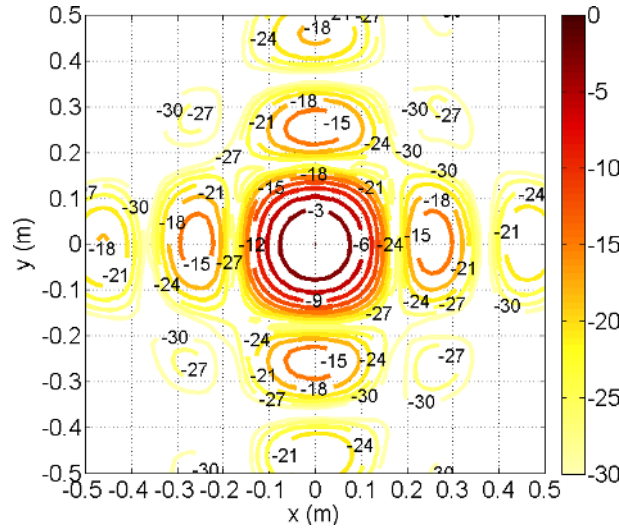


Fig. 3. The normalized power density radiated at the focal plane by an 8x8 NFF array as that in Fig. 2.

III. TECHNOLOGIES FOR MICROWAVE NFF ANTENNAS

NFF antennas can be realized through a number of different technologies and layouts, which can be classified as proper modifications of those that are extensively used to implement conventional FF-focused antennas.

NFF arrays essentially exploit the extreme flexibility of the antenna arrays to control the side lobe level, shape the -3 dB focal spot, implement multi-focus NFF antennas, and electronically scan the focal point. A number of planar and linear microstrip arrays have been designed and characterized for wireless links at 2.4 GHz, 5.8 GHz, X-band. With respect to conventional unfocused microstrip arrays, NFF arrays simply require for an adjustment of the microstrip feeding network.

Fresnel zone plate lens antennas [45]-[46], transmitarrays [47] and reflectarrays [50]-[52] have also been considered to implement NFF planar lens antennas, which can be considered as devices that are able to shape the phase-front of the electromagnetic field radiated by a conventional feed antenna. All of them are suggested to avoid the complexity and losses introduced by the feeding network of electrically large NFF microstrip arrays. In transmitarrays and reflectarrays, the required phase shift is obtained by properly modifying one or more geometrical parameters of the unit cell of the quasi-periodic transmitting/reflecting surface.

NFF antenna solutions also include pyramidal or conical horns with a dielectric lens in front of the antenna aperture, ellipsoidal reflector antennas, leaky-wave (LW) antennas. A classical approach to focus the radiated field at a point in the antenna NF region consists in a curved LW guiding structure [18]. To avoid a bulky curved guiding structure, a tapered rectilinear LW guiding structure can be used [57], [58]. A NFF LW antenna can also be obtained by using non-periodic scatterers embedded in a scatterer layer, which cause the scattering of the evanescent wave propagating along a waveguide layer, in such a way that the scattered fields sum constructively at the selected focal point [63]-[64]. In NFF LW antennas, the inherent dispersion feature of the leaky mode allows for the frequency-scanning of the focal point.

Finally, NFF antennas made by slotted waveguide antennas [43]-[44], radial line slot antennas and arrays of open-ended waveguides have also been proposed. Indeed, when compared with printed antenna technology, waveguide antennas show a better efficiency and a higher power handling. More recently, NFF antennas using dielectric resonator antennas [55]-[56] and the surface integrated waveguide (SIW) technology [61]-[62] have also been investigated.

IV. NFF ANTENNAS FOR SHORT-RANGE WIRELESS SYSTEMS

When compared to conventional FF-focused antennas, the advantages in terms of radiated power density levels (Fig. 2), as well the spatial resolution guaranteed by the smaller size of the spot region around the field amplitude peak (Fig. 3), make the NFF antennas attracting for a number of wireless systems.

A. Wireless remote identification systems

In some RFID (Radio Frequency Identification) applications, the expected location of the tagged item is so close to the reader antenna that the tag actually lies in the reader antenna NF-region. Then, a NFF RFID reader antenna can be beneficial with respect to a conventional FF-focused antenna. Indeed, for an assigned EIRP (Effective Isotropic Radiated Power) allowed by regulations (4 W and 3.2 W, for FCC and ETSI regulations at the UHF band, respectively), the percentage of tags read successfully in the region of interest (for example at the center of an RFID portal in a warehouse) increases if a higher power density impinges on the tags. On the other hand, by reducing FF-radiation the multipath phenomena will be attenuated as well, which are the main causes for the distortion of the reader coverage area in indoor scenarios. Moreover, field focusing in UHF-RFID reader antennas can help

to both reduce the interference between adjacent RFID portals in large warehouses and bound the reader interrogation volume at a specific section of a conveyor belt along which the tagged items move. In both previous scenarios, a NFF antenna can limit the false positive readings (cross readings), as well as the personnel radiation hazards.

A number of NFF arrays have been proposed for fixed RFID readers: planar arrays [41], [49], [53], [54], and reflectarrays [52] at 2.4 GHz; circular arrays [26], dielectric resonator antenna arrays [55]-[56] and dielectric resonator transmitarrays [47], for RFID readers at 5.8 GHz; dual-band NFF reflectarrays operating at 915 MHz and 2.4 GHz [50], [51].

A NFF array can also be used in identification systems for through-gate access control, which use RFID, WLAN (Wireless Local Area Network), or mobile phone frequency bands [40].

B. Industrial microwave applications

In non-contact non-destructive microwave material inspections, a focused field is effective to increase the sensor sensitivity when either measuring small spatial variations of the material characteristics in large samples or testing small material samples [38], [45]-[46]. NFF arrays can also be used for temperature sensing by microwave radiometry [39]. Other applications are about industrial microwave heating, subsurface probing, concealed weapon detection, foreign object detection inside lossy media [23], plasma heating [7], non-lethal microwave weapons, short range high-data-rate point-to-point communications.

C. Local hyperthermia and imaging systems

Focusing techniques have been applied for a long time in biomedical engineering, to improve spatial resolution in imaging systems or to increase the temperature in size-limited spot regions. Indeed, in microwave hyperthermia applicators, the deposited power density must be maximized in a limited spot area around the diseased tissue, without overheating the surrounding healthy tissues [16], [24], [32], [44]. Further applications could be in communication/tracking systems for wireless endoscopic capsules or in antennas for remote monitoring of vital signs [48].

D. Wireless power transfer systems

In non-radiating wireless power transfer systems, both the receiving and transmitting antennas are required to have a size comparable to the operating distance [31]. Then, in those applications where the above distance cannot be sufficiently small, a radiating coupling is a mandatory solution, and a NFF antenna can increase the power transfer efficiency at the receiving antenna when compared to a conventional FF-focused antenna [20]-[21], [25]. Multi-focus NFF antennas could also be applied in multi-point wireless power charging systems for mobile electronic devices, or in smart antennas for simultaneous wireless information and power transfer.

E. NFF antennas in antenna measurement facilities

NF-focusing of large phased arrays has been proposed for performing adaptive array nulling tests by conveniently resorting to interference sources located in the antenna NF-region instead of interference sources located in the far field of the unfocused phased array [17]. Indeed, it is known [3], [4], [10], [15], that in the focal plane, near the antenna axis, a NFF antenna exhibits a FF-like radiation pattern that looks like the FF-pattern of the unfocused version of the same antenna, when the focal point moves from the FF-region towards the antenna aperture up to a distance no lower than the antenna aperture. As an example, Fig. 4 shows the normalized power density of the above 8×8 NFF patch array, at different distances from the array plane, for a uniform amplitude excitation. It is apparent that a FF-like pattern (namely a pattern with deep nulls and a small beamwidth) only appears close to the focal plane, while such feature is lost when the observation plane moves either close to array plane or into the antenna FF-region.

Additionally, it is worth noting that the plane-wave generators used for antenna testing and radar cross section measurements in compact anechoic chambers [11]-[12] belong to the class of NFF antennas exhibiting a specific NF shaping, namely, a local plane wave field in the targeted quiet zone.

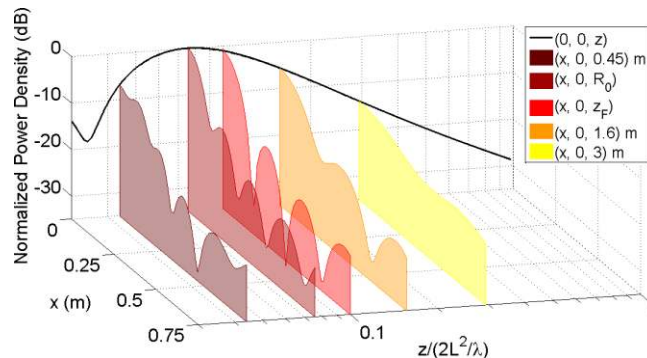


Fig. 4. The normalized power density radiated by an 8×8 NFF array as that in Fig. 2, along the direction perpendicular to the array surface (z -axis, solid line) and along the transverse direction (x -axis), at different distances from the array xy -plane: $z = \{0.45 \text{ m}, R_0 = 0.775 \text{ m}, z_F = 1 \text{ m}, 1.6 \text{ m}, 3 \text{ m}\}$.

V. SYNTHESIS TECHNIQUES FOR NFF ANTENNAS

The methods used for the synthesis of NFF antennas can be classified into two classes: the conjugate-phase approach and the multi-objective optimization techniques. As already stated in Sect. II, in the conjugate-phase approach, the phase of the excitation of each antenna radiation source is set to compensate for the phase delay introduced by the path between the source and the assigned focal point, to achieve a constructive interference of all the contributions at the focal point. Additionally, a proper tapering of the amplitude of the source excitation can be chosen to control the level of the secondary lobes around the focal spot region. Otherwise, if a multi-objective optimization technique is applied, it means that both the amplitude and phase of the source excitations are simultaneously determined through *ad-hoc* optimization techniques.

The conjugate-phase approach has a clear physical meaning based on a ray-optics model (Fig. 1). On the other hand, the optimization-based approaches are much more general and flexible, in that they allow to concurrently optimize many NFF antenna parameters, for almost arbitrary antenna configurations and complex application scenarios. As for example, optimization-based approaches can be applied to the synthesis of: NFF arrays with unequal elements, NFF antennas radiating in lossy and/or non-homogeneous media, antennas radiating in presence of scatterers in their NF region, NF/NF or NF/FF multi-focus antennas, plane-wave generators.

Throughout the present review, the attention is mostly devoted to NFF antennas for which the antenna size, L , and the distance between the focal point and the radiation sources on the array/antenna aperture are both greater than the free-space wavelength, λ . Then, it is assumed that the focal point is located in the antenna radiative NF region. Additionally, it is required that $R_F < 2L^2/\lambda$ ($\gamma = R_F/(2L^2/\lambda) < 1$), as the focusing advantages quickly diminish as the focal point $F(x_F, y_F, z_F)$ moves far from the antenna. It follows that results and design guidelines summarized in the present review may not apply to antennas for some specific applications. Among them, it is worth mentioning low-frequency compact antennas used to concentrate the electromagnetic energy at very short distances in lossy media (hyperthermia, buried object detection), antennas for either HF RFID readers or NF UHF RFID readers, antennas used to generate collimated beams in the antenna reactive near-field region, wearable antennas for intra-body communications.

In the following, design guidelines for NFF antennas are discussed by referring to some simple formulas derived for a planar array. However, it is apparent that most of the results and discussions also apply to aperture antennas or any other antenna where the radiated fields can be conveniently expressed in terms of properly sampled equivalent surface currents.

A. The conjugate-phase approach

Let us consider an array of N radiating elements distributed in a $L_x \times L_y$ area on the xy plane of a rectangular coordinate system, whose position \underline{r}_n is denoted by $(x_n, y_n, 0)$ with $n=1, 2, \dots, N$ (Fig. 5). As usually done in antenna array analysis, it is assumed that: (a) all the elements are identical with the same spatial orientation; (b) the element spacing is larger than half-wavelength, so that the mutual coupling effects can be neglected. The electric field radiated by the array at the observation point $P(x, y, z)$ in the antenna radiative NF region can be expressed as:

$$\underline{E}(\underline{r}) = \sum_{n=1}^N C_n \underline{E}_n(\underline{r}) = \sum_{n=1}^N C_n \underline{E}_0(\theta_n, \phi_n) \frac{e^{-j2\pi|\underline{r}-\underline{r}_n|/\lambda}}{|\underline{r}-\underline{r}_n|} \quad (1)$$

where $C_n = A_n e^{j\varphi_n}$ denotes the complex excitation coefficient of the n -th array element. In (1), $\underline{E}_0(\theta_n, \phi_n)$ is the vector electric field that an array element located at the origin of the coordinate system would radiate at a distance $R = |\underline{r}| = \sqrt{x^2 + y^2 + z^2}$ in the direction (θ_n, ϕ_n) of the vector $(\underline{r} - \underline{r}_n)$, normalized with respect to the spreading factor $e^{-j2\pi R/\lambda} / R$. For each array element, only the far-field contribution is included in (1), as it has been supposed that $|\underline{r} - \underline{r}_n| > \lambda$, namely the observation point is located in the FF-region of each array element. It is worth underlying that, for a given observation point, the direction of the electric field vector and the effect of the element radiation pattern, at that point, both depend on the array element that is being considered. This explains why in (1) the dependence of the vector \underline{E}_0 on (θ_n, ϕ_n) has been highlighted. Focusing the field in (1) at a focal point $\underline{r} = \underline{r}_F = R_F \hat{r}_F$ by resorting to the conjugate-phase approach results in:

$$\varphi_n = +\frac{2\pi}{\lambda} |\underline{r}_F - \underline{r}_n| = \frac{2\pi}{\lambda} \sqrt{R_F^2 + |\underline{r}_n|^2 - 2R_F \hat{r}_F \cdot \underline{r}_n}, \quad (2)$$

and

$$\underline{E}(\underline{r}) = \sum_{n=1}^N A_n \underline{E}_0(\theta_n, \phi_n) \frac{e^{-j2\pi(|\underline{r}-\underline{r}_n| - |\underline{r}_F - \underline{r}_n|)/\lambda}}{|\underline{r} - \underline{r}_n|} \quad (3)$$

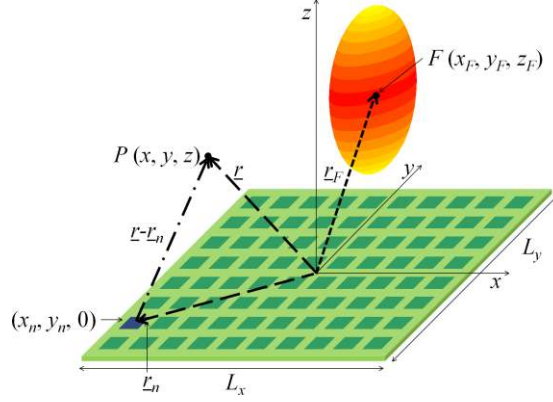


Fig. 5. Geometry of a NFF planar array, with a sketch of the ellipsoid-shaped focal region.

If the focal distance R_F is enough larger than the antenna size L , the phase tapering required for focusing at the focal point F can be approximated by the sum of a linear phase shift plus a quadratic term (Fresnel approximation):

$$\varphi_n \approx -\frac{2\pi}{\lambda}(\hat{r}_F \cdot \underline{r}_n) + \frac{2\pi}{\lambda} \frac{|\underline{r}_n|^2}{2R_F} \quad (4)$$

In (4), the linear phase shift corresponds to that one required to point at the focal point direction (θ_F, ϕ_F) when the focal point is beyond the FF-region boundary. Note that in (4) the constant phase term $(-2\pi R_F/\lambda)$ has been removed, as it is irrelevant. Going closer to the antenna aperture (up to the minimum distance where only the radiative field components can be considered for each array element), the exact expression for the conjugate-phase profile (2) should be used. The quadratic phase approximation guarantees an error less than $\pi/8$ if $R_F > \sqrt[3]{L^4/8\lambda}$, whenever the antenna size, L , is greater than a few wavelengths.

Due to the field spreading factor $1/|\underline{r} - \underline{r}_n|$, the peak of the radiated power density does not occur at the focal point where all field contributions sum in phase, but it is located at a point between the antenna aperture and the focal point [10], [42]. Indeed, when moving from the focal point toward the antenna aperture, array contributions does not sum in phase anymore; on the other hand, the expected amplitude reduction is over-compensated by the fact that each element contribution exhibits a higher amplitude close to the antenna aperture, as the factor $1/|\underline{r} - \underline{r}_n|$ increases. The focal shift vanishes as $\gamma = R_F/(2L^2/\lambda)$ reduces [42].

While the phase tapering is essential to focus the radiated field at the focal point, the amplitude tapering can be used to reduce the secondary lobe level. Indeed, a high level of the secondary lobes around the focal spot may degrade measurement accuracy in non-contact sensing applications, or heat healthy tissues in microwave hyperthermia systems. Also, high sidelobes may reduce transmission efficiency in wireless power transfer systems, increase the interference with nearby wireless systems, raise the personnel exposure to radiation hazards, enlarge the number of false positive readings in RFID systems. In [10], it was observed that an amplitude tapering that gives lower transverse sidelobes also yields higher forelobes and aftlobes along the aperture axis. As far as the transverse plane patterns are concerned, array synthesis techniques used for conventional FF-focused arrays can be applied to reduce the side lobe level [15], [28]. Indeed, as already stated, an array NF pattern approximately equal to an assigned FF pattern is obtained once the phase focusing is added to the synthesized FF-focused equivalent array. Moreover, Graham [9] suggested a technique to synthesize a given axial pattern around the focal point, starting from the expressions of classical amplitude taperings used for the transverse plane pattern synthesis. A Dolph-Chebyshev amplitude tapering and a quadratic phase profile have been applied to achieve the desired side lobe level at the focal plane of linearly-polarized NFF planar microstrip arrays, at 10 GHz [28]. The radiation pattern results confirm that the field radiated by a NFF antenna at the focal plane, near the axis of the antenna, has the same properties of the FF radiation pattern of the corresponding FF-focused array [3], [10], [15]. In [29], an asymmetrical excitation amplitude has been combined with a conventional Dolph-Chebyshev amplitude tapering, to reduce the sidelobe level in a NFF linear array of dipoles even when the beam is steered from the broadside direction.

While the side lobe level can be controlled by the amplitude tapering in both aperture antennas and arrays, the grating lobes come out from the discrete character of the arrays, and they appear in NFF arrays too. It is well-known that unequally spaced arrays are effective to mitigate the grating lobe phenomenon in FF-focused phased arrays, as an alternative to uniform dense arrays. In this context, a numerical performance analysis of a 2.4 GHz NFF linear array has been presented in [30], where the array elements

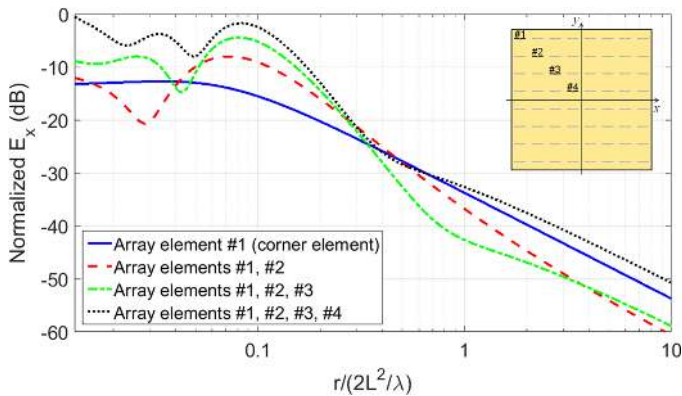
are spatially distributed according to a binary tree fractal. Also, in [8], a procedure for the joint optimization of both the position and complex amplitude excitation of the array elements has been setup, to design linear NFF arrays with reduced sidelobes and grating lobes. Simulated results for linear arrays of half-wavelength dipoles can also be found in [19], where the quadratic phase profile is compared against an antisymmetric progressive phase shift, in terms of the -3 dB spot size.

At the focal point, (3) reduces to:

$$\underline{E}(\underline{r} = \underline{r}_F) = \sum_{n=1}^N A_n \underline{E}_0(\theta_n, \phi_n) / |\underline{r}_F - \underline{r}_n|. \quad (5)$$

It is apparent that, depending on the array element polarization and orientation, the vector electric field contributions at the focal point may not be aligned along the same direction (polarization mismatching). Moreover, each contribution is weighted by the radiation pattern of the array element at the focus direction (see the dependence of each term by (θ_n, ϕ_n) in (5)). To get the maximum value of the amplitude of the sum in (5), a constructive *vector* summation of all the contributions is required (polarization matching), with all contribution directions in the array element main beam, as it happens in the FF-region wherein parallel-ray approximation is valid. In the antenna NF-region, one or both above conditions may not be satisfied, so determining a loss in terms of the field amplitude at the focal point and around it as well. The above loss with respect to the achievable maximum value is more apparent when the focal point moves closer to the antenna surface or the focal point is out of the antenna aperture axis, or high-directivity array elements are used. As an example, Fig. 6 shows how a set of array elements contribute to the electric field components of an 8x8 NFF array of short dipoles parallel to the x-axis. The interelement spacing is $d = 0.8\lambda$, along both x-axis and y-axis, and the normalized focal distance is $\gamma = R_F / (2L^2/\lambda) = 0.1$, where it has been assumed $L = 6.4\lambda$. The considered array elements are four dipoles along the array diagonal. Each curve is obtained by adding a new element contribution, starting from that of the element at the array corner (continuous line). All curves are normalized to the maximum amplitude of the E_x component when all four contributions are added (dotted line). It is apparent how each new contribution adds in phase with the previous ones around the focal region, while this does not happen in the FF region where the focusing effect is lost. As expected, the cross-polar component E_y and the longitudinal component E_z exhibit an amplitude decay rate greater than the 20dB/decade value of the co-polar component E_x . However, both E_y and E_z exhibit a not negligible relative amplitude in the NF region, so confirming that part of each element vector contribution is lost due to the above mentioned mismatching polarization phenomenon. For the numerical case here considered, the effect of the radiation pattern is negligible due to the relatively wide beamwidth of a short dipole.

For an assigned polarization requirement at the focal point, the field amplitude reduction can be partly compensated by a proper orientation of each array element. Some papers on circular arrays of dipoles [26]-[27] have discussed how the dipole orientation (radially oriented, collinearly oriented, tangential to the array ring) affects the focusing performance. The field amplitude loss at the focal spot due to the polarization mismatching is also discussed in [58], where an array of eight radially-oriented linearly-polarized rectilinear LW antennas is used to implement a planar NFF antenna. To increase the focal power density in a linear array, in [31], a set of high directive printed Yagi-Uda antennas have been rotated so that each one points at the focal point, so eliminating the loss due to the radiation pattern effect.



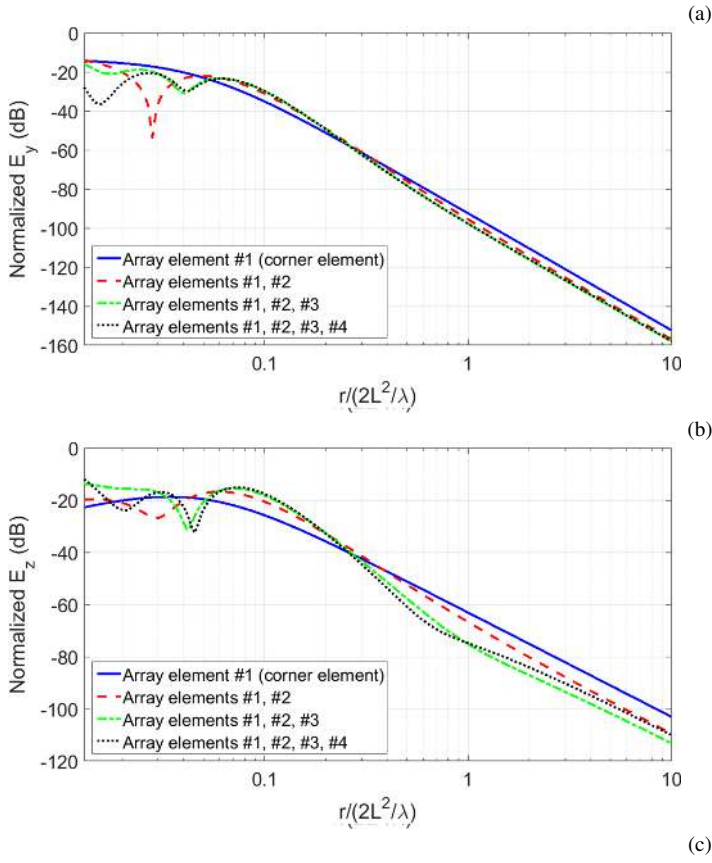


Fig. 6. Amplitude of the (a) E_x , (b) E_y and (c) E_z components of the electric field radiated by an 8x8 NFF array of x-aligned short dipoles (see the inset geometry), when the field contributions are added starting from the element #1 up to the element #4. All curves are normalized to the maximum amplitude of the E_x component radiated by all four dipoles.

Fig. 7a shows simulation results for the phase of the x -component of the electric field (E_x) radiated by an 8x8 NFF array as that in Fig. 2, in a plane orthogonal to the antenna aperture and passing through the focal point (yz -plane in Fig. 5). The phase distribution of the electric field has been calculated around the -3 dB focal spot. As expected [7], [18], [38], a locally plane wavefront can be observed around the focal point. Incidentally, the results in Fig. 7 suggest that the conjugate-phase approach could be used as an effective initial guess in iterative techniques for the synthesis of plane-wave generators. In Fig. 7b, the instantaneous value of the E_x component shows the converging (diverging) behavior of the wavefront before (after) the focal plane at $z = R_f = 8.2\lambda$.

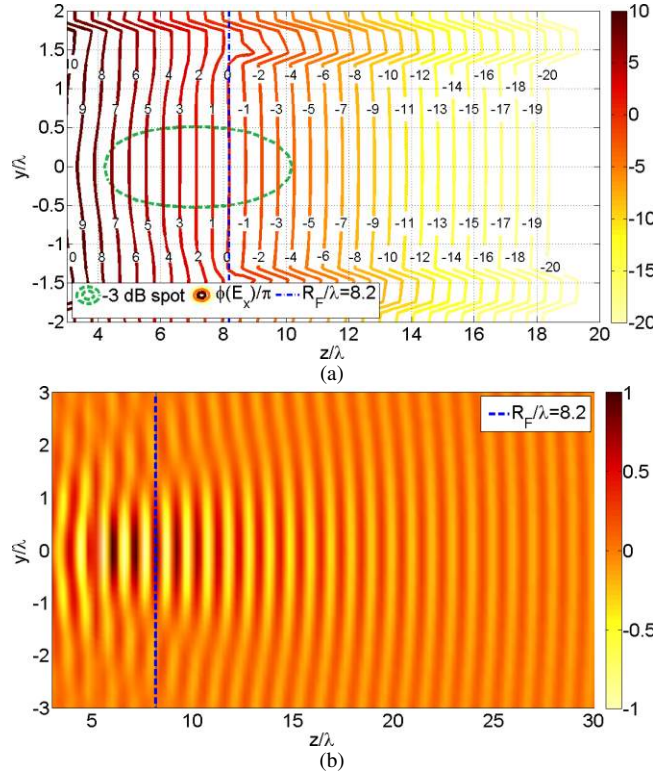


Fig. 7. The electric field component along the x -direction (E_x) radiated by an 8×8 NFF array as that in Fig. 2, in the yz -plane: (a) phase normalized to π and (b) normalized instantaneous value. The focal distance $R_F = 8.2\lambda$ and the -3 dB spot of the electric field module are also indicated in the figure.

In those applications where the focal spot region is required to move during the system operations (scanning process in material characterization measurements, RFID tagged item localization/tracking [26]), a NFF phased array is required, which needs for a number of phase shifters and their related control network. In this context, a circular phased array can be advantageously adopted when the focal spot is required to move along the direction normal to the array surface [26]–[27]. Indeed, only one phase shifter for each array ring is required, as all the array elements on the same ring are equidistant from the focal point. Therefore, $N-1$ phase shifters are needed for a circular array made of N rings. In this context, a 4 dB improvement in terms of field amplitude increase at the focal spot region has been obtained in [27], by using a collinear orientation of the dipoles instead of the radial orientation, at the expenses of a slight larger DoF . The focusing effect of a Gaussian amplitude tapering combined with a quadratic phase profile has been numerically studied in [59], when considering a focused circular aperture with radiating elements arranged on a polar lattice.

B. Multi-objective optimization techniques

In most of the applications listed in Section IV, the main objective of the NFF antenna is maximizing either the electromagnetic power density or the amplitude of a specific component of the electric/magnetic field, in a size-limited spot region close to the antenna aperture. However, some applications may require additional specific features for the antenna near field. The simultaneous focusing at different target areas, a proper near-field shaping around the focal spot, a simultaneous control of the NF radiation and FF pattern, are only a few of the additional features that may be required to profitably extend the applicability of NFF antennas. Therefore, the problem to be solved by the antenna designer is a typical optimization problem with a set of constraints, where the degrees of freedom are represented by the array/aperture layout and geometrical parameters, and the phase and amplitude profiles of either the array currents or the antenna aperture field. Focusing the field at a focal point by implementing the conjugate-phase profile in (2) and possibly combining it with pattern synthesis techniques can be considered as an effective zero-order solution for the design of a NFF antenna. On the other hand, the implementation of specific features of the antenna near field unavoidably demands for advanced synthesis techniques. The latter are also required to account for higher-order effects: the presence of inhomogeneous materials or obstacles in the volume surrounding the antenna and the focal spot region; the mutual coupling between the elements of a NFF array; the mutual coupling between the NFF antenna and the receiving antenna.

Narasimhan *et al.* [13] presented a unified approach for the synthesis of the near field radiated by uniformly- or nonuniformly-spaced arrays of sources located on a contour of arbitrary shape. The proposed technique is based on expressing the assigned near-field (both amplitude and phase patterns) in terms of the coefficients of spherical vector wave functions and then solving a set of linear equations. Later on, Narasimhan [14] used a least squares procedure to accurately reconstruct the near field (amplitude and phase patterns) from a discrete set of field samples selected at Nyquist interval over a spherical surface with a radius equal to the

prescribed NF distance at which the field has to be synthesized.

In the context of the synthesis techniques for NFF arrays, Álvarez *et al.* [34] proposed an optimization framework based on the iterative Levenberg-Marquardt algorithm, to minimize the level of the secondary lobes around the focal spot region and reduce the focal shift. Both amplitude and phase of the array weights (as well as phase only) are determined by imposing the minimization of a cost function related to the maxima and minima bounds allowed for the electric field square amplitude at a set of test points in the array NF region. It is worth noting that the synthesis procedure can also include the position and orientation of each array element as additional degrees of freedom [36]. Moreover, the mutual coupling between the array elements can be considered in the optimization process, by including a coupling matrix in the NF evaluation, to relate the actual array element currents to the array port excitations [37].

In some applications, the NFF antenna can be required to focus on two or more target simultaneously. As for example, in Fig. 8, the normalized power density radiated by an 8×8 NFF array as that in Fig. 2 has been evaluated at the plane $z = 8.2\lambda$ for the case of two focal points: $F_1(0, 0, 8.2\lambda)$ and $F_2(-4\lambda, -5\lambda, 8.2\lambda)$. The array element excitations have been calculated as the sum of the two complex excitations required in case of a single focal point at F_1 and F_2 , respectively. The -3 dB spot diameter in correspondence of F_1 is still $W_1 = 14.7$ cm as for the single focal point case (see Fig. 3). Around the focal point at F_2 , the intensity of the power density is lower and the focus width measured at the plane parallel to the antenna aperture is apparently larger. This suggests that, although the focalization effect at two focal points can be achieved by a simple superposition principle, an optimization approach is required if more stringent specifications must be met.

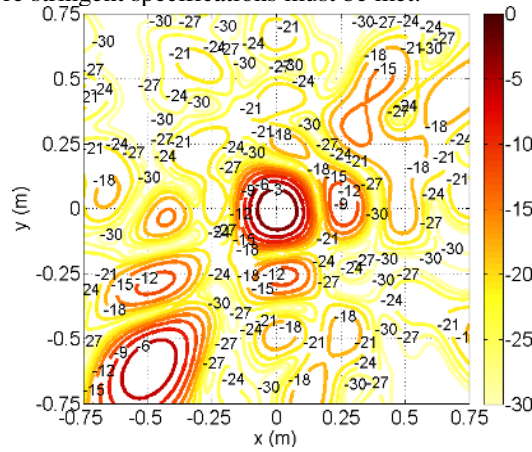


Fig. 8. The normalized power density radiated at the plane $z = 8.2\lambda$ by an 8×8 NFF array as that in Fig. 2, with two assigned focal points: $F_1(0, 0, 8.2\lambda)$ and $F_2(-4\lambda, -5\lambda, 8.2\lambda)$.

In this context, the same approach as in [34] has been applied to the synthesis of multi-focus NFF planar arrays in [33], [35]. A flexible cost function establishes the allowed minimum and maximum field bounds for different points in the targeted NF-region. Proper error rates are also introduced, which can also account for the minimization of the focal point displacement, the 3D spot sizes and the field amplitude difference among the assigned focal points. The method can deal with the optimization of both magnitude and phase of the array feeding currents [35], as well as phase only [33], [35]. The extreme flexibility of the proposed synthesis framework allows to add further requirements for the array near-field shaping besides multi-focusing, as for example a vanishing field amplitude at one or more points close to the antenna where either an obstacle/scatterer or a high-sensitivity device could be located [35].

In the context of optimization techniques for NFF antennas, a different goal may be the maximization of the power transfer efficiency between the NFF antenna to be designed and a receiving test antenna located at the assigned focal point. As far as aperture antennas are concerned, some seminal papers are those from Bickmore [1], Kay [2] and Borgiotti [6]. In [2], [6], the authors deal with a theoretical analysis of the power transfer efficiency between two aperture antennas with known aperture fields, which are faced to each other in the Fresnel region. For two rectangular apertures, in [6], the complex aperture field that maximizes the power transfer efficiency is explicitly derived. It results that the optimal profile of the field amplitude on the rectangular apertures is given by prolate spheroidal wave functions. Moreover, the derived optimal phase solution is a quadratic phase profile as that in (4), namely each aperture must be focused on the center of the other one [2], [6].

An optimal design procedure to maximize the power transmission efficiency between an N -element NFF array and a test receiving antenna located at an assigned focal point has been presented by Shan and Geyi [20]. The power transmission efficiency, namely the ratio between the power received at the matched test antenna and the array input power, is expressed in terms of the scattering matrix of the corresponding network made of $N+1$ ports. By imposing the maximization of the power transmission efficiency, an eigenvalue problem is derived, whose solution gives the optimal complex excitations for the array elements. Such NFF array synthesis technique is apparently more general than the conjugate-phase approach. Indeed, it allows accounting for both the effects of the mutual coupling between the array elements and among the two antennas as well, and the presence of either

obstacles or an inhomogeneous medium in the region around the two antennas, for completely arbitrary array geometries. Three 4×4 planar microstrip arrays have been designed, at 2.4 GHz, with interelement separation of 6 cm, and required focal distance equal to 10, 15 and 20 cm, respectively. The receiving antenna is supposed to be a patch identical to those used for the NFF planar array. Not surprisingly, an almost quadratic phase profile is determined by the optimal procedure (as predicted in [2], [6]), which is due to both the low mutual coupling effects and the absence of obstacles between the NFF array and the test antenna.

In [16], an approach similar to that in [20] was formerly applied to the synthesis of NFF arrays for hyperthermia applications. There, the eigenvalue problem is obtained by imposing the maximization of the ratio between the field square amplitude at the designed focal point (which is proportional to the specific absorption rate - SAR) and the array input power. Numerical results are shown for a hexagonal array of 19 linearly polarized elements that radiate in presence of a lossy media modeling the human tissues. As in [20], numerical results show the existence of a focal shift even for the optimal solution. Indeed, a maximization of the squared amplitude of the electric field at the assigned focal point (normalized to the array input power) does not implicate that the latter is the maximum field amplitude point in its surrounding region [16].

It has to be underlined that just a few of the studies on the power transfer efficiency between two antennas in the Fresnel region consider the coupling phenomena in a lossy media (instead of free-space coupling). On the other hand, including the effect of lossy media around the focused antenna is essential when designing antennas for detection, sensing and imaging in lossy media (as for example, human body tissues and terrain), or antennas for hyperthermia. A numerical study based on the solution of a generalized eigenvalue equation has been presented in [22], to derive the optimal field distribution on a transmitting aperture which maximizes the power transfer efficiency, when the propagation occurs in a lossy medium. A comparison against a uniform unfocused aperture field is also shown, as a function of the size of the two apertures and the separation distance. The effectiveness of the optimal aperture field has been validated through a numerical analysis of the power transfer variations induced by the presence of a metallic sphere between the two aperture antennas [23], as the model was studied for a system devoted to foreign object detection in lossy media. The synthesis technique presented in [20] has been applied to the optimal design of a NFF array for microwave-induced hyperthermia at 433 MHz [24]. Numerical simulations for the SAR in the array NF-region are validated against measurements with an array prototype radiating close to a 20 cm-high glass tank filled with a homogeneous human-body mimicking material.

More recently, a synthesis technique for shaping the power density radiated by a planar microstrip array around the focal spot has been presented in [48]. The excitation phases of the array elements are determined by the minimization of a cost function through the steepest descent method (SDM), whereas the conventional conjugate-phase profile has been chosen as the initial guess of the iterative synthesis procedure. A further synthesis technique for NFF planar arrays is shown in [49], where a set of global basis functions (each one representing a field focused at a point of an assigned plane parallel to the array) is used to synthesize a NF contoured pattern in the target area close to the antenna aperture. The complex amplitude of the above basis functions is derived via a least squares method. Simulation results are shown for a set of arrays of CP microstrip patches, for RFID applications at 2.4 GHz. The synthesis technique in [49] has also been applied to shape the near-field of a 2.4 GHz RFID 13×13 planar microstrip array [54]. The final goal was to achieve an almost constant field amplitude, with a small ripple, in a plane parallel to the array and located at 1 m far from it.

A further synthesis problem related to the shaping of the near-field radiated by an array arises when a local plane-wave field must be generated in an assigned volume (quiet zone). Such a NFF array can be an alternative to reflector or lenses in antenna-pattern characterization, radar cross section measurements, electromagnetic susceptibility testing. In this case, the objective is to minimize phase and amplitude oscillations in a set of planes close to the array surface, while minimizing the field outside the quiet zone to reduce multipath interferences [11]-[12].

Finally, in [60] the required near-field (any source-free solution to the Maxwell's equations) is firstly transformed into the corresponding far-field. Then a global optimization technique based on genetic algorithms is used to derive the position, orientation and excitation of an array of short dipoles that can synthesize the above far-field. By using a set of simple dipole antennas, it has been shown that the near-field radiated by the above synthesized array can give a satisfactory approximation of the initial near-field specification.

VI. CONCLUSIONS

Near-field focused antennas are receiving a considerable attention in short-range wireless microwave systems as they can be an advantageous solution with respect to conventional far-field focused antennas, in all those applications where electrically large microwave antennas can still meet physical size requirements. The 3D size of the - 3 dB focal spot, the focal shift, the focusing gain and the level of the secondary lobes around the focal spot region are the metrics used to characterize NFF antennas. Nonetheless, the antenna gain and radiation patterns can also be important in some near-field applications, even if they are far-field parameters. Indeed, a low far-field radiation is often required to a near-field focused antenna in addition to the intensification of the radiated field around the focal point. Moreover, the polarization and the cross-polar level of the radiated field around the focal spot may require a specific attention in those applications where either the receiving antenna or the scattering object located at the focal spot are sensitive to the incident field polarization. Differently from conventional far-field focused antennas, a non-uniform orientation of the radiating element of an antenna array can be effective to improve the focusing performance. Additionally, due to the strong dependence of the antenna near-field on the surrounding objects/materials (as for example the body

tissues in local hyperthermia, or the conductive object an RFID tag is attached to), the synthesis of near-field focused antennas in free-space could lead to a reduced performance of the system performance with respect to what expected. Then, depending on the required focal distance, operating frequency and application scenario, numerical models and synthesis techniques should include the above environment coupling effects into the optimization process. The phase-conjugate concept remains the basic design criteria for near-field focused antennas. On the other hand, when designing multi-focus antennas and antennas radiating in complex lossy scenarios, or when a specific near-field shaping is required, more general multi-objective optimization techniques are mandatory. Nonetheless, in the context of the iterative synthesis techniques, the phase-conjugate solution may represent an effective initial guess to start with.

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