# Sparse Array of Dielectric Resonator Antennas for Ultra-Wide Band Applications

*(Invited Paper)*

Lucas H. Gabrielli, Luciano P. de Oliveira, Gilliard N. Malheiros-Silveira,
Julián L. Pita, Hugo E. Hernandez-Figueroa
School of Electrical and Computer Engineering
University of Campinas
Campinas, SP, 13083-852, Brazil
E-mail: lucashg@fee.unicamp.br

***Abstract*—We present our latest advances in antenna miniaturization using dielectric resonators and design of sparse arrays for ultra-wide band applications without the need for non-linear numerical optimization. We experimentally demonstrate a dual-feed, low-profile, stacked dielectric resonator antenna for the C band with wide bandwidth and high gain, as well as a bio-inspired sparse array design for ultra-wide band applications. We show that the results presented can be successfully extended to other frequency windows, in particular the near-infrared range, where specific issues prevent the use of more conventional antenna and antenna array designs.**

## I. Introduction

Miniaturization is an ever-present goal in antenna design. Applications such as mobile technology, airborne radars, satellite communications, and embedded systems, all benefit from smaller and lighter antennas. However, miniaturization must not impact radiation efficiency, frequency bandwidth, polarization, radiation profile, or any other requirements imposed by the system design, resulting in a complex process often executed by trial and error.

A promising technique for the design of small antennas is the use of leaky dielectric resonators. The study of ceramic resonators as antenna elements started in the 80s, where the analysis of their modes, radiations patterns, and techniques of excitation made it clear that dielectric resonators could be used as antenna radiators, offering an alternative to the traditional low-gain radiators [1]–[3], since they present several interesting advantages over metallic antennas such as low loss, high radiation efficiency, increased impedance bandwidth and absence of surface waves [4]. The radiating properties of dielectric resonators started being thoroughly exploited in the past few years, particularly due to improvements in fabrication technology, which fuelled an ever-present demand for low-profile high-gain antennas. Besides the aforementioned characteristics, the dielectric resonator antenna (DRA) can be designed to operate over a wide range of frequencies—from 1 GHz up to 50 GHz—and several feeding mechanisms, such as probes, microstrip lines, slots, etc., can be used to properly excite the DRAs, making them easy to integrate with several technologies.

The reduced size is particularly important in beam-forming applications where a large number of elements may be required and production costs could become an issue. In such cases, the use of sparse arrays can also decrease the total payload represented by the antenna system without changing its effective aperture and directivity, particularly in the case of heavier dielectric materials. Nonetheless, the design of sparse arrays is also a complex task, where improper antenna placement results in severe secondary lobe levels. The absolute majority of techniques for the design of 2-dimensional sparse arrays use some sort of non-linear numerical optimization applied to thinned arrays [5], [6], aperiodic tilings [7], [8] or fractal structures [9]–[14], which demand high computational power and little insight into why each proposed solution works or how to further improve them.

In this work we present our advances in miniaturized DRAs in microwaves and their extended use up to optical frequencies. We propose and experimentally characterize a dual-feed, low-profile, stacked DRA for the C band with wide bandwidth of 33.2% and high gain of 8.38 dBi. Targeting both optical and microwave sparse arrays, we also propose and experimentally demonstrate a bio-inspired sparse array pattern that enables ultra-wide band (UWB) operation without the appearance of strong secondary lobes. We show that the same array pattern can also enable the use of optical phased arrays for near-infrared communications with current micro- and nano-fabrication technology.

## II. Stacked dielectric resonator antenna

In order to design a miniaturized DRA with wide bandwidth and high gain, a low-loss dielectric with high permittivity is necessary [15]. We use the dielectric mixture $[Bi_2O_3\text{-}Fe_2O_3]_x[Al_2O_3\text{-}CaO\text{-}TiO_2]_{1-x}$ with $\varepsilon_r = 10$ to form the 2 cylindrical stacked resonators illustrated in fig. 1 with dimensions $h_1 = h_2 = 12.0\,\text{mm}$, $a_1 = 9.0\,\text{mm}$, and $a_2 = 11.5\,\text{mm}$. The $HE_{11\delta}$ resonant modes are excited by single or dual side probes fed through the bottom metallic plate with side $\frac{\lambda}{4}$ at the central frequency. The length and distance of the probes control the tunning of the antenna, as also does the gap between the resonators. This gap is made of a 1 mm-thick nylon disk with small radius.

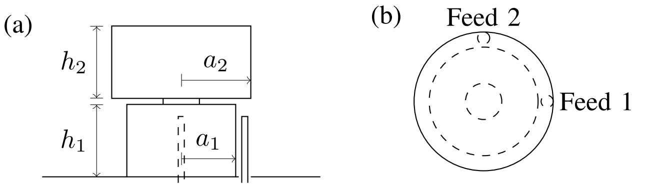


Figure 1. Geometry of the DRA from the (a) front and (b) top views.

With a single feed in place, the proposed DRA achieves a relative bandwidth of 33.2% around 4.08 GHz, more than twice the complete C band range (3.625 GHz–4.2 GHz) at the −15 dB level, in good agreement with the numerical simulations, as shown in fig. 2. Also matching the simulations, the measured gain is 8.38 dBi, 2 dBi above the theoretical estimation [16]:

$$G = \frac{\pi^2}{\varepsilon_r} + \frac{2\pi}{\sqrt{\varepsilon_r}} \quad (1)$$

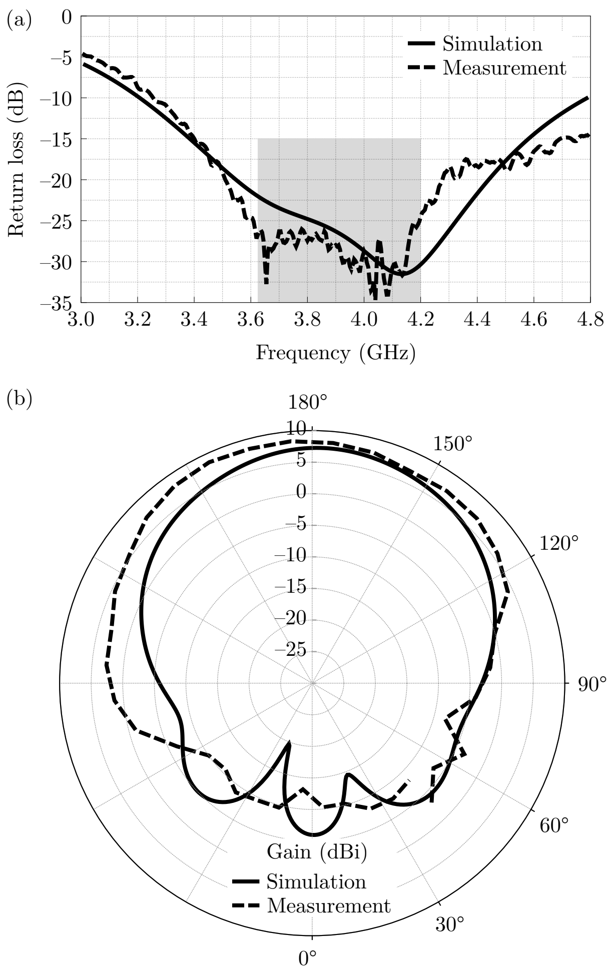


Figure 2. Stacked DRA characteristics with a single feed: (a) return loss and (b) gain pattern.

In the dual feed configuration, the DRA supports 2 linearly polarized independent radiation modes. The individual excitation probes are accessed by overlaid striplines, leading to a small return loss difference between them, as presented in fig. 3. The experimental results show very wide bandwidth (still more than twice the C band range in each mode) for −15 dB return loss.

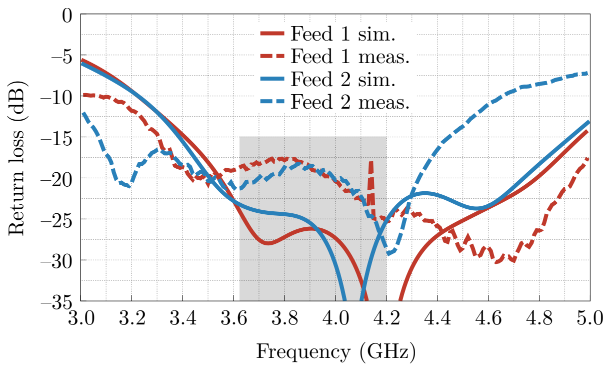


Figure 3. Return loss for each mode in the dual-feed stacked DRA.

## III. Optical Dielectric Resonator Antenna

The advantages brought about by DRAs in microwave frequencies can be explored in other frequency ranges as well. In particular, for near infrared and visible wavelengths metals present high losses, significantly lowering the radiation efficiency of common metallic antenna geometries. The use of dielectric materials, on the other hand, is encouraged due to the high permittivity and transparency of the materials used in the complementary metal-oxide-semiconductor (CMOS) technology and III-V platform for active devices. It follows as a natural design choice for optical nano-antennas the techniques developed for DRAs in microwaves [17].

Leveraging this know-how, we have proposed compact nano-DRAs for the C band in optical communications (wavelengths between 1530 µm and 1565 µm) based on Si [18] and GaAs [19]. When working in the optical domain, the main difference in the antenna design lies in the feeding structure, which cannot be as intricate or small with respect to the wavelength as in microwaves because of limitations in the fabrication. Mode and phase matching between the resonant mode and the guided wave also becomes important, otherwise the dielectric resonator cannot be excited in the correct mode.

Nevertheless, the design equations for the resonator and main radiation characteristics remain the same, providing the same level of miniaturization and bandwidth found in microwave DRAs.

## IV. Sparse Array Design

Miniaturized antennas play a key role in large arrays for high directivity and advanced beam forming capabilities. In order to minimize cost, complexity, weight, and power loss, the number of array elements can be reduced and their distance increased, resulting in thinned or sparse arrays. However, the placement of each element must be carefully evaluated lest strong side lobes emerge on the array factor. This complex analysis is more often than not performed by numerical non-linear optimization algorithms, which lead to little insight into the solution itself.

Alternatively, we propose the use of a bio-inspired array pattern known as Fermat's spiral [20]. The advantages of this distribution of elements is that it ensures constant average distance between radiators without any periodicity and maximal packing efficiency [21], [22], without the need for numerical computations, since the position of each antenna is given analytically by:

$$\rho_n = \frac{d}{d_{14}}\sqrt{n} \tag{2}$$

$$\phi_n = n\pi\left(3-\sqrt{5}\right) \tag{3}$$

where $(\rho_n, \phi_n)$ are the cylindrical coordinates of the $n$-th antenna in the array for $n = 1, 2, \ldots$, $d_{14} = \sqrt{5 - 4\cos\phi_3}$, and $d$ the minimal distance between elements.

The theoretical array factor characteristics for Fermat's Spirals of varying sizes and with $d = 30\,\mathrm{cm}$ can be seen in fig. 4. It is easy to see that the proposed array reaches UWB performance even with a relatively small number of elements. Increasing this number improves both the absolute values of directivity and secondary lobe level, and their variation across the whole frequency range.

The choice of $d$ is merely an example, since the results presented can be scaled to other frequencies with a inversely proportional change in $d$ (e.g. if $d$ is halved, the frequencies would be doubled). We also note that the frequency window presented does not cover the whole bandwidth of the array, which is computationally expensive to calculate, and which is probably much wider than shown. In fact, the limiting factor for any practical application of the proposed array will probably be the bandwidth of the individual radiators, as in the case of our proposed DRA.

To demonstrate the performance of Fermat's spiral, we have measured the array factor at the visible wavelength of $\lambda = 633\,\mathrm{nm}$. The antennas used were large square apertures defined over a spacial light modulator (SLM) with $d = 581\lambda$, representing an extreme case that would be difficult to optimize using numerical algorithms. The aperture array was illuminated by an expanded laser beam. The reflected light passed through a lens that performed a far-field transformation and it was finally recorded by a CCD sensor. The use of a grating pattern in each aperture allows us to measure the reflected signal away from the reflection of the main bean, otherwise the main beam would dominate the whole image.

The extracted secondary lobe levels for numbers of elements varying between 4 and 64 are presented in fig. 5 together with the theoretical calculations. The deviation from the theoretical predictions for arrays with more than 36 elements is due to the limited width of the illuminating beam, which leads to a power imbalance between the central and peripheral antennas, and teh limited resolution in positioning the apertures in the pixel grid of the SLM.

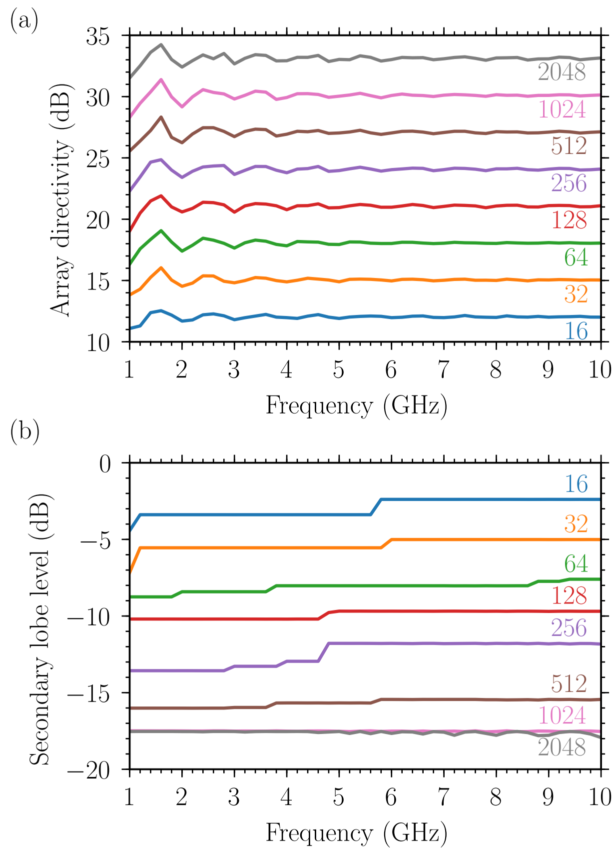


Figure 4. Calculated array factor characteristics for Fermat's spirals with $d = 30\,\mathrm{cm}$ for varying numbers of elements: (a) directivity and (b) secondary lobe level.

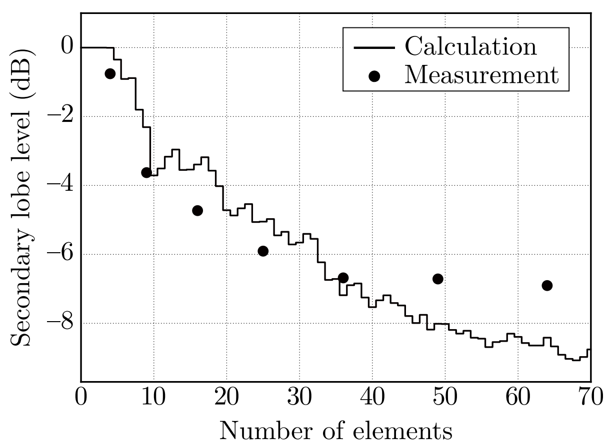


Figure 5. Measured secondary lobe level for Fermat's spirals with $d = 581\lambda$ for varying numbers of elements.

Similarly to the DRA, the ideas developed for Fermat's spiral array in microwaves are also useful in the optical domain. Optical antenna arrays cannot be formed with distance between elements on the order of their operation wavelength due to fabrications constraints. The distance between radiators in near infrared is usually around tens of wavelengths, leading to the generation of multiple radiation lobes with the same intensity as the main one [23]. This issue is immediately eliminated by the use of aperiodic arrays, in particular, the proposed Fermat's spiral [20].

## V. Conclusion

Miniaturization of antennas for large arrays is a recurrent goal in antenna systems design. We have shown that DRA represent a viable alternative for miniaturization without impact in gain and bandwidth by using high permittivity and low loss dielectrics. The proposed antenna has low-profile and possibility for dual feeding while simultaneously maintaining high gain and wide bandwidth, covering more than twice the C band.

Although miniaturization is important for large arrays, the added weight of the dielectric material can be problematic, thus sparse arrays are preferable specially in the case of transported systems (both surface and airborne). In order to overcome the usual necessity of complex and time-consuming non-linear optimization algorithms to design sparse arrays with low secondary lobe levels, we propose the use of Fermat's spiral as a layout for the distribution of antennas. We show that this shape provides excellent results both in terms of secondary lobe levels and directivity over more than a decade frequency bandwidth. This solution is immediately available for any UWB application, leaving the limit in bandwidth of operation solely in terms of the radiating element.

Finally, we demonstrate how both proposals scale to other frequency ranges, in particular the near infrared domain, where they provide solutions to the technological challenges specific to that part of the electromagnetic spectrum.

## Acknowledgment

This work is supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) project no. 446746/2014-2, Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) project no. 2012/22517-2, and the Brazilian Science and Technology Institute FOTONICOM (CNPq project no. 574017/2008-9 and FAPESP, project no. 2008/57857-2).

## References

[1] S. Long, M. McAllister, and L. Shen, "The resonant cylindrical dielectric cavity antenna," *IEEE Transactions on Antennas and Propagation*, vol. 31, no. 3, pp. 406–412, May 1983.

[2] M. McAllister, S. Long, and G. Conway, "Rectangular dielectric resonator antenna," *Electronics Letters*, vol. 19, no. 6, p. 218, Mar. 1983.

[3] M. McAllister and S. Long, "Resonant hemispherical dielectric antenna," *Electronics Letters*, vol. 20, no. 16, p. 657.

[4] K. W. L. Kwai Man Luk, Ed., *Dielectric Resonator Antennas*, ser. Antennas. Research Studies Press, Jun. 2002, vol. 11.

[5] R. L. Haupt, "Thinned arrays using genetic algorithms," *IEEE Transactions on Antennas and Propagation*, vol. 42, no. 7, pp. 993–999, Jul. 1994.

[6] M. Bray, D. Werner, D. Boeringer, and D. Machuga, "Optimization of thinned aperiodic linear phased arrays using genetic algorithms to reduce grating lobes during scanning," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 12, pp. 1732–1742, Dec. 2002.

[7] T. Spence and D. Werner, "Design of Broadband Planar Arrays Based on the Optimization of Aperiodic Tilings," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 1, pp. 76–86, Jan. 2008.

[8] ——, "Multiobjective optimization in the design of broadband arrays based on aperiodic tilings," in *IEEE Antennas and Propagation Society International Symposium, 2008. AP-S 2008*, Jul. 2008, pp. 1–4.

[9] Y. Kim and D. Jaggard, "The fractal random array," *Proceedings of the IEEE*, vol. 74, no. 9, pp. 1278–1280, Sep. 1986.

[10] J. Bogard and D. Werner, "Optimization of Peano-Gosper fractile arrays using genetic algorithms to reduce grating lobes during scanning," in *Radar Conference, 2005 IEEE International*, May 2005, pp. 905–909.

[11] J. Petko and D. Werner, "The evolution of optimal linear polyfractal arrays using genetic algorithms," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 11, pp. 3604–3615, Nov. 2005.

[12] V. Pierro, V. Galdi, G. Castaldi, I. Pinto, and L. Felsen, "Radiation properties of planar antenna arrays based on certain categories of aperiodic tilings," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 2, pp. 635–644, Feb. 2005.

[13] J. Petko and D. Werner, "The Pareto Optimization of Ultrawideband Polyfractal Arrays," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 1, pp. 97–107, Jan. 2008.

[14] T. Spence and D. Werner, "Generalized Space-Filling Gosper Curves and Their Application to the Design of Wideband Modular Planar Antenna Arrays," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 12, pp. 3931–3941, Dec. 2010.

[15] H. Rocha, R. Sohn, A. Sombra, F. Freire, M. da Silva, M. Santos, T. Cordaro, and C. Junqueira, "Bandwidth enhancement of stacked dielectric resonator antennas excited by a coaxial probe: an experimental and numerical investigation," *IET Microwaves, Antennas & Propagation*, vol. 2, no. 6, pp. 580–587, Sep. 2008.

[16] A. Petosa, *Dielectric Resonator Antenna Handbook (Artech House Antennas and Propagation Library)*. Artech House Publishers.

[17] G. N. Malheiros-Silveira, L. H. Gabrielli, C. J. Chang-Hasnain, and H. E. Hernandez-Figueroa, "Breakthroughs in Photonics 2013: Advances in Nanoantennas," *IEEE Photonics Journal*, vol. 6, no. 2, pp. 1–6, Apr. 2014.

[18] G. N. Malheiros-Silveira, G. S. Wiederhecker, and H. E. Hernández-Figueroa, "Dielectric resonator antenna for applications in nanophotonics," *Optics Express*, vol. 21, no. 1, p. 1234, Jan. 2013.

[19] G. N. Malheiros-Silveira and H. E. Hernandez-Figueroa, "Dielectric Resonator Nanoantenna Coupled to Metallic Coplanar Waveguide," *IEEE Photonics Journal*, vol. 7, no. 1, pp. 1–7, Feb. 2015.

[20] L. H. Gabrielli and H. E. Hernandez-Figueroa, "Aperiodic antenna array for secondary lobe suppression," *IEEE Photonics Technology Letters*, vol. 28, no. 2, pp. 209–212, Jan. 2016.

[21] J. Ridley, "Packing efficiency in sunflower heads," *Mathematical Biosciences*, vol. 58, no. 1, pp. 129–139, Feb. 1982.

[22] R. V. Jean, *Phyllotaxis: A Systemic Study in Plant Morphogenesis*. Cambridge University Press, Jan. 1994.

[23] J. Sun, E. Timurdogan, A. Yaacobi, E. S. Hosseini, and M. R. Watts, "Large-scale nanophotonic phased array," *Nature*, vol. 493, no. 7431, pp. 195–199, Jan. 2013.