Terahertz and Optical Dielectric Resonator Antennas: Potential and Challenges for Efficient Designs

Christophe Fumeaux[1], Chengjun Zou[1], Daniel Headland[1], Shruti Nirantar[2], Philipp Gutruf[2], Longfang Zou[3], Madhu Bhaskaran[2], Sharath Sriram[2], Withawat Withayachumnankul[1]
[1] The University of Adelaide, Adelaide, Australia, christophe.fumeaux@adelaide.edu.au
[2] RMIT University, Melbourne, Australia
[3] Centre for Bio-inspired Technology, Imperial College, London, UK

***Abstract* — The unique characteristics of Dielectric Resonator Antennas (DRAs) make them suitable for various niche applications throughout the spectrum, from microwave frequencies to the optical regime. One of the striking features of DRAs is their high efficiency when the resonator is realized in low-loss high-permittivity dielectric material. This interesting property arises from their radiation mechanism being mostly based on displacement currents, and opens the door to efficient device realizations towards higher frequencies where conductor losses degrade the performance of metallic resonators. This paper will highlight some of the distinctive properties of the DRAs and review their potential applications in various frequency regimes. It will in particular consider the latest developments at THz and optical frequencies, with high-efficiency realizations of reflect-arrays and magnetic mirrors.**

***Index Terms*—Dielectric Resonator Antennas, Optical Antennas, Nano-Photonics.**

I. Introduction

The concept of Dielectric Resonator Antenna (DRA) has been first proposed by Long et al. [1] in 1983, and has since then attracted steadily increasing research attention in the antenna community. The operation of DRAs as radiators exploit the "radiation losses" of dielectric resonators made of moderate to high relative permittivity ($5 < \varepsilon_r < 100$) when excited in their lower-order resonant modes in an open environment. Various attractive properties of this type of antennas have been extensively documented such as their high design versatility, wide bandwidth and compact size [2]. Remarkably, one of the most striking properties of DRAs was already prominently identified in the original article [1]: DRAs can be very efficient radiators at the highest frequencies relevant for antenna technologies. Indeed, DRAs are intrinsically relatively immune to ohmic losses, which can drastically affect the performance of metallic resonators at millimeter-wave frequencies and above. In this context, this paper will briefly review various developments of DRAs throughout the radio-frequency spectrum, and extend the considerations to the terahertz and optical regimes, where downscaled realizations of this type of radiators offer the promise of efficient antennas, phased arrays and reflect-arrays. The potential and challenges associated to realizations in the optical regimes will be discussed in the second part of the paper.

II. DRAs at Microwave and Millimeter-Wave Frequencies

A. Microwave DRAs

The developments of DRAs since the 1980s have resulted in a large number of geometries and feeding methods. As reviewed e.g. in [2], numerous realizations of DRAs as single elements or in array configurations, have demonstrated the versatility of this type of antennas, which typically combine compactness and wide bandwidth of operation. Nevertheless, the additional complexity in terms of manufacture compared to planar metallic antennas have to date hindered the widespread commercial application of DRAs.

In terms of efficiency, DRAs realized in low-loss material have been demonstrated to achieve above 98% efficiency in the low GHz range as measured in [3]. This however often does not provide a decisive advantage compared to corresponding planar resonant metallic designs, which remain generally efficient in the microwave range.

Recent developments seem to indicate that the DRAs might be best suited for various niche applications, where their specificity and advantages can be fully expressed. For example, the use of various orthogonal modes in a single antenna volume for multi-function and diversity applications [4-8] can be mentioned, or the realization of compact ultra-wideband designs [9, 10], or the integration of the DRA in available dielectric structures [11, 12].

B. Millimeter-wave DRAs

The millimeter-wave range is characterized by increased conductor losses arising from the skin effect. For this reason, the efficiency of planar metallic antenna starts to perceptibly deteriorate as the frequency increases in the millimeter-wave range. In contrast, it has been validated in [13] that the efficiency of DRAs remains well above 90% at 35 GHz, indicating that the losses in the metallic ground plane are not significant contributors to efficiency degradation. Further early implementations at 40 GHz [14], 60 GHz [15] and 94 GHz [16] confirmed high efficiency of the DRAs, with the major source of losses attributed to feeding structures. This indicates the real potential of DRAs for millimeter-wave applications, while the main challenge for widespread use remains the integration of the dielectric resonator as integral part of the millimeter-wave circuit. The technological advances however have recently offered path to solve this issue, with recent realizations demonstrating high-efficiency millimeter-wave DRAs using flip-chip assembly [17] and bonding techniques [18], substrate perforation [19], micromachining [20], as well as integration in standard LTCC [21] or CMOS technologies [22]. Such new approaches are likely to nurture the potential of the DRAs as efficient millimeter-wave radiators.

III. Terahertz DRAs

The proven high-efficiency of millimeter-wave DRA in both single-element and array configurations provides the rationale to extend their range of applications in the terahertz regime, i.e. at frequencies from roughly 300 GHz to 10 THz. This has been suggested by researchers in the past, for example in [23], as a means for mitigating the high-losses in terahertz and infrared reflectarrays. The numerical investigation [24] based on realistic dispersive conductor models predicted that terahertz passive DRAs could be designed with near 100% efficiency for application as reflectarray elements.

This prediction of high DRA efficiency at terahertz frequencies was recently confirmed in [25]: A magnetic mirror with near unity reflectivity has been experimentally demonstrated for operation at a center frequency of 0.8 THz. This magnetic mirror was operated at the fundamental magnetic dipole resonance of passive cylindrical dielectric resonators, periodically arranged in a uniform reflectarray. These identical cylindrical DRAs were etched from a single-crystal silicon wafer (ε_r = 11.68) bonded onto a gold ground plane (Fig. 1). Details of the unconventional fabrication method can be found in [25]. It is noted that the large scale realizations are possible, and that patterning is not limited to uniform configurations. For this first experimental demonstration, the individual DRA elements were designed with a height of 50 μm, diameter of 100 μm, and were arranged in a square lattice with 150 μm periodicity. The measurement of a realized prototype established the magnetic mirror operation in a 30% fractional bandwidth. The measured efficiency was determined to be near unity, i.e. within the measurement uncertainty of the 97% efficiency predicted from numerical analysis. A crucial aspect for attaining this high performance is the bonding of the DRA on the metal ground, which is realized as an ultra-thin (<500 nm) SU-8 layer. Simulations and early prototypes suggested that a thick bonding layer will degrade the efficiency significantly as such a layer can be a non-negligible source of dielectric losses at terahertz frequency.

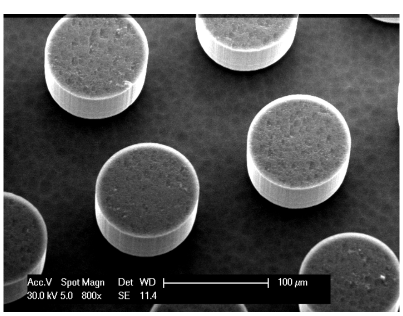

Fig. 1. Partial view of an array of single-crystals silicon DRAs bonded on a metal ground, for operation as magnetic mirror at 0.8 THz.

These measurements demonstrate that the DRA should be considered as a potentially nearly lossless resonant element in terahertz phased arrays. Alternatively, the exploration reconfigurability mechanisms for the reflectarray elements could offer capabilities of beam steering in narrow band applications.

IV. Optical DRAs

The strongly dispersive properties of metal conductivity at optical frequencies results in the so-called plasmonic behavior which can be the source of substantial dissipation losses. For most noble metals, the plasmonic effects manifest themselves mostly at infrared and visible frequencies. Considering the resilience of DRAs to losses in their ground plane, it has been postulated that acceptable efficiencies could be preserved up to the optical domain, allowing the realization of optical DRAs. The availability of efficient sub-wavelength resonant elements is highly desired as such elements can hugely benefit future applications requiring high-resolution manipulation of light.

The numerical investigation presented in [24] indicated that a resonant low-loss dielectric cylinder on a silver ground plane should retain an efficiency of above 80% up to the near-infrared regime. The study also predicted a rapid degradation as the wavelength becomes shorter than 1 μm, indicative of intrinsic limitations in performance arising from plasmonic effects as the frequency increases in the visible range. In effect, the plasmonic effects shorten the effective wavelength in the resonator and this precludes a straightforward scaling of the design from microwave frequencies. Furthermore, the interaction of the resonator with the metal plane also introduces losses which will progressively reduce the achievable efficiency on resonance as the frequency increases.

An experimental realization of a reflectarray of TiO_2 cylinders on a silver ground plane was presented in [25] and is consistent with these findings. The possibility of generating a marked resonance in passive nano-scale dielectric resonators on a metal plane at visible frequencies was demonstrated at 633 nm wavelength, but the efficiency dropped below 50%.

Further challenges in the implementation of DRAs in the optical domain include the selection of the dielectric material [27]. This aspect requires considerations including effect from dispersive and anisotropic properties, influence of the underlying metal as well as manufacturability. To illustrate the tolerances associated with nano-scale fabrications, a profile measured on a manufactured array of TiO2 resonators on a silver substrate is shown in Fig. 2. It is noted that the moderate Q-factor of dielectric resonators becomes advantageous to broaden the resonance, thus relaxing tolerances.

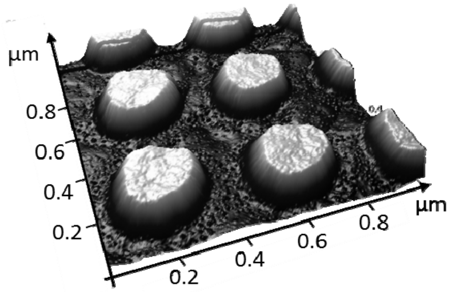

Fig. 2. Atomic force microscopy measurement of an array of TiO_2 DRAs on a silver substrate for resonance at 633 nm.

In terms of application in the optical domain, DRAs appear mostly suitable for beam manipulations, e.g. in reflectarray configurations [26], or as coupling structure for surface plasmon polaritons [28] or guided waves. Whereas the efficiency will remain acceptably high in the infrared range despite plasmonic losses, visible frequency implementations can generally benefit from all-dielectric implementations. In this case, the magnetic and electric resonant modes of dielectric resonators can be exploited to create Huygens' unidirectional scattering, as recently demonstrated in [29, 30]. Concepts aiming at introducing tunability in these designs are currently the topic of extensive research [31, 32], with one of the aim being to achieve optical beam steering. The success of these efforts will be paramount to future applications of optical DRAs for light manipulation.

V. Conclusion

This paper has reviewed the applications of DRAs in different spectral ranges. Despite the scalability of the concept, specific properties of dielectric resonators are expressed differently in various frequency ranges. In particular, the possibility to achieve nearly lossless resonances in the millimeter and terahertz range suggests a high potential for application of DRAs in short-distance high-data-rate communication systems. Further up in frequencies, DRAs scaled to infrared and visible wavelength might emerge as efficient elements to create optical devices for future nano-photonics applications.

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