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Opportunities, Progress and Challenges in Active Heatsink Antenna Arrays for 5G and Beyond

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Abstract — **The conventional air and liquid cooling based thermal management strategies in mm-wave active phased arrays are illustrated with several examples from the literature. The key role of antenna engineers in electronics thermal management is discussed. The intriguing concept of using the antennas as auxiliary heat dissipators is recapitulated with a focus on the past and recent developments. The multiphysics (electromagnetic and thermal) modeling and design approaches of such dual function antennas are outlined. Some of the future multidisciplinary research challenges in heatsink antennas are identified.**

Keywords — **antennas, electronics cooling, millimeter wave technology, phased arrays, thermal management.**

I. Introduction

The short-term predictions on power consumption reveal that the 5G/6G mm-wave base stations will play a major role, while causing high service costs and environmental pollution [1]. Due to the low efficiency of the silicon-based beamformer integrated circuits (ICs) at mm-wave frequencies [2] and the extreme heat density generation in small chip areas, maintaining safe temperature levels across the active antenna arrays becomes the ultimate challenge.

Thermal management can (i) improve the reliability of the ICs, (ii) reduce the static power consumption (caused by the leakage current) of the chips, (iii) ease the temperature-dependent calibration issues (caused by the thermal-related drifting of the phases/amplitudes), and (iv) improve the device lifetime [3], [4]. As a rule of thumb, it is commonly accepted that the average IC junction temperature should be kept below 125^{o}C under typical working conditions at steady state for a safe and reliable device operation [5], and that every 10^{o}C rise in the temperature reduces the average life of the chip by 50% [6]. Passive cooling is generally preferable for cost, energy consumption and reliability reasons.

In a small-cell single-user communication scenario using the most advanced chip implementation techniques of today at 30 GHz, about 1-2W of heat is generated per cm^2, while only about 0.25W/cm^2 can be cooled passively, unless there is space for a direct connection between the chips and a large heatsink [7]. As a result, the heat gets trapped in the center of the array, resulting in an unacceptable temperature rise above 300^{o}C, even in the presence of a large heatsink surrounding the array [8]. The cooling issue gets more severe for the non-line-of-sight coverage and multiple-beam generation requirements of the near-future systems due to much larger power demand. It is evidenced and agreed in the community that the currently proposed amplifiers and processors need significant power efficiency improvement and innovation in their cooling system before being operational on the market [9]. The major design limitation in the state-of-the-art active phased arrays is that the electromagnetic (EM) and thermal parts are considered separately, and the cooling devices are seen as add-ons, which is far from optimal.

One of the original concepts for cooling enhancement is to use the antenna element/array itself as a heatsink and achieve dual (EM-thermal) functionality in a compact design. Especially in the past few years, there has been a growing trend in the concept of “heatsink antennas” [10]. However, a careful review of the literature reveals that there is a very weak (and only conceptual) link between antenna-oriented research and thermal-oriented research.

The aims of this paper are to highlight the need of dual function antennas for mm-wave applications, to discuss the progress in their multiphysics modeling/design, and to identify the future research challenges in the light of the state of the art. The rest of the paper is organized as follows. Section II demonstrates the conventional active cooling techniques applied to mm-wave phased arrays. Section III provides a review on heatsink antennas, with a critical discussion on their modeling and design. Section IV presents the conclusions.

II. Conventional Cooling Concepts in Active Phased Arrays at mm-Waves

Although not shown in most of the antenna literature, the IC-integrated array designs at mm-waves has to include an integrated cooling structure, which is very much dependent on the antenna-IC integration technique [11] (traditional or planar approach, flip-chip based, embedded-IC etc.). Since the heat generation per unit volume is too large, in general, the cooling units become predominant as compared to the antenna boards.

Fig. 1 shows various examples of active (forced air, liquid) cooling systems applied to mm-wave phased arrays. The first three examples (a)-(c) demonstrate forced air cooling via fans, while the last three examples (d)-(f) show forced liquid cooling via pumps, which is more effective in temperature reduction than the air cooling.

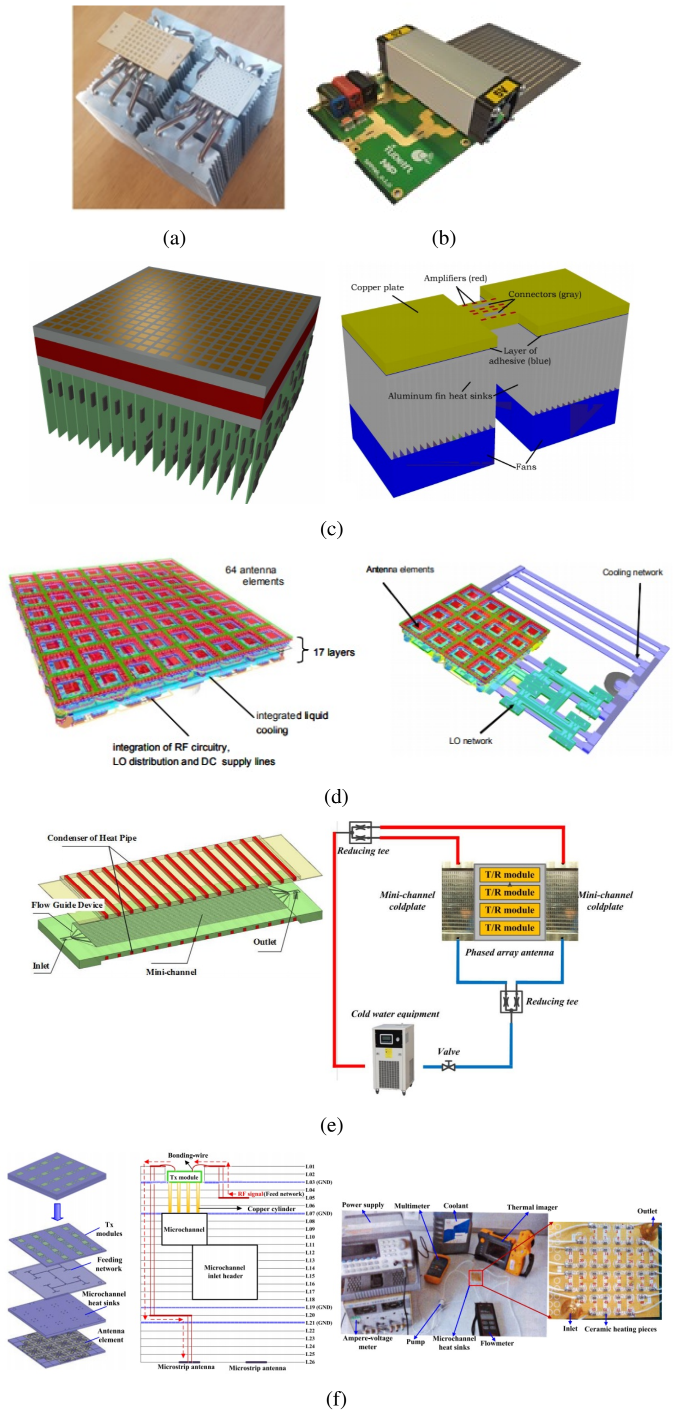

Fig. 1. Examples of cooling modules in active mm-wave phased arrays: (a) 28 GHz arrays from TU Eindhoven/NXP with the CPU cooler module (fans are not shown) [12], (b) 28 GHz array of TU Delft/NXP with the cooling unit having fans on both sides [13], (c) forced air cooling concept in DLR's 30 GHz array [14], (d) liquid cooling system in IMST's 30 GHz array [15], (e) cold water equipment and mini-channel cold plate based cooling of a Ka-band array [16], (f) microchannel heatsink based cooler in a 30 GHz array [17].

These examples clearly reveal that it requires a much larger space than the antenna arrays themselves to insert the add-on cooling devices (heatsinks, fans, water equipments). There is also a large cost/complexity for the transfer of heat to the external cooler. This raises weight and cost issues, as well as leading to serious reliability, maintenance and energy consumption problems, which is in conflict with the requirements of mass-market active phased arrays (i.e. low-profile, affordability, versatility).

It is apparent that the currently proposed amplifiers and processors need significant power efficiency improvement and some innovation in their cooling system before being operational on the market. The main flaw in these common cooling approaches in the literature is that the IC cooling is done only on one side. In other words, the potential of heat removal via EM radiators is ignored.

III. Achieving Dual Functionality: Heat Dissipating Antennas

In conventional active antenna designs, IC cooling is achieved on the surface of the front-end components or on the side of the electronics with rapid heat transfer by conduction or convection. In general, the antenna is not designed to dissipate heat. However, exploiting the antenna surface by forming it as a heat sink creates an additional cooling path, and eases the thermal problem in mm-wave ICs. In turn, the stringent requirements on the size, weight, energy consumption and maintenance of the cooling systems illustrated in Fig. 1 can be relaxed. In this section, different examples of heatsink antennas from the literature are reviewed, together with a discussion on their EM-thermal modeling and future challenges.

A. Review of the Past and Recent Developments

The heatsink antenna concept was introduced in the field more than a decade ago, which was brought back to the development of active mm-wave arrays as a promising cross-disciplinary solution. The first relatively straightforward designs were based on thick-ground planes [18], [19] and thermal vias between the patch and IC [20], which were followed by more complex extruded-finned [21], [22], fractal [23] and cube [24] heatsinks placed on top of patch antennas, mostly below 6 GHz. More recently, different 3D antenna elements/arrays that function as a heatsink were studied, such as stepped-notch [25], inverted-F [26], horn [27] and Vivaldi [28], at higher frequencies. In fact, 3D antennas has now become more affordable thanks to additive manufacturing.

Fig. 2 shows several examples of existing active heatsink antenna element/array designs. In the literature, the major focus of such designs is on the EM aspects, however, in a few works, maximal temperature comparison with and without the heatsink is also provided. The EM and thermal performance of the relevant studies are summarized in Table 1.

B. Thermal Modeling and Multiphysics Optimization

In the literature, the thermal performance of heatsink antennas was quantified by experiments [20], conduction-based simulation models with rough estimation of heat transfer coefficients [27], [28] or computational fluid dynamics (CFD) based simulations with air flow rate assumptions [25], [26]. There was no consideration of IC's thermal characteristics in the simulations, except the total heat power generated.

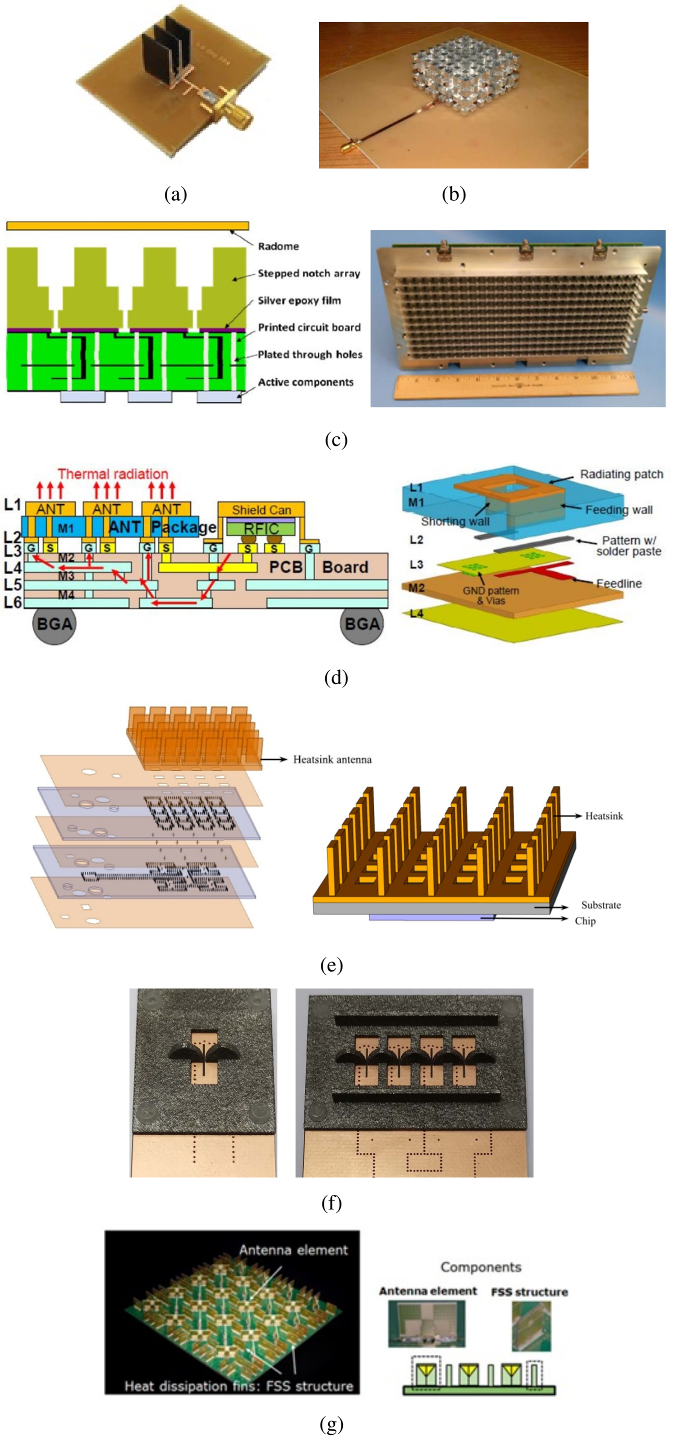

Fig. 2. Active heatsink antenna and array designs in the literature: (a) extruded-fins on top of a patch at 6 GHz [22], (b) cube-based fractal antenna at 1.4 GHz [23], (c) stepped notch array at 12-17 GHz band [25], (d) metal stamped antenna-in-package at 28.5 GHz band [26], (e) horn-like elements at 60 GHz band with an open-ended waveguide and two vertical fins [27], (f) fin-shaped Vivaldi antenna and its array at 22.5-30 GHz band [28], (g) concept of NEC based on fin-like antenna elements employing Split-Ring structures and additional metal plates employing FSS on them for EM transparency [29].

Recently, a compact thermal model (CTM) for the ICs was proposed in [10] which is complemented by conduction-based simulations and verified by the readings from the temperature sensors embedded within the ICs. Although the model was seen to provide a useful initial guess of the maximal IC temperature at the steady state [12], the results were not very accurate across the array, and the transient phenomena was not considered. It is worth to note that several dynamic thermal modeling techniques were also proposed in the literature [30], [31], yet there is no universal methodology as the ones for the static models [32], [33]. Besides, the thermal and EM simulations in the heatsink antenna literature are not coupled. Therefore, the effect of possible temperature changes on the IC behavior, antenna matching and radiation characteristics are not considered. However, to improve the performance predictability, a few coupled EM-thermal multiphysics models were studied in the community [34], [35].

Table 1. Classification and EM comparison of heatsink antennas

Type	Ref.	Topology	Freq. (GHz)	Number of Elements	Peak Gain (dBi)	-10 dB Impedance Bandwidth (GHz)	Temp. Decrease (^oC)
3D heatsink on top of an antenna	[20]	Patch with thermal via	2.0	1	3.9	0.03 (1.5%)	37
	[21]	Patch with finned heatsink	2.4	1	4.1	0.04 (1.8%)	N/A
	[22]	Patch with finned heatsink	5.8	1	6.3	1.02 (17.6%)	N/A
	[23]	Patch with fractal heatsink	1.4	1	7.2	0.04 (2.8%)	N/A
	[24]	Patch with cube heatsink	23.8	1	4.9	1 (4.2%)	N/A
3D antenna as a heatsink	[25]	Stepped-notch	13.2	24×11	N/A	5 (37.9%)	N/A
	[26]	Inverted-F	28.5	1×8	13.78	0.7 (2.45%)	11
	[27]	Step-profiled horn	60	4×4	18.8	7 (11.7%)	40
	[28]	Vivaldi	25	1×4	15.5	7.2 (28.8%)	18

C. Open Challenges

At the current stage, a proper mm-wave thermal modeling in active antennas is missing. The performance trade-offs of heatsink antenna concepts in mm-wave bands and for large phased arrays are not known. The optimality of the proposed approaches in terms of joint EM-thermal performance is not clear. These create an obscurity in the application of the heatsink antenna concepts to large phased arrays at mm-wave bands that require large bandwidth, wide-angle scanning, high gain, low interference and dual-polarization from the EM perspective, and large cooling capacity and temperature uniformity from the thermal perspective.

Therefore, the are many open challenges that need to be addressed in the near future, including original research on:

- Proper and accurate thermal modeling of active IC-integrated array antennas by means of implementing new compact/dynamic networks describing the heat spreading and removal efficiently,
- Coupled EM-thermal modeling/optimization techniques,
- Designing heatsink/heat-exchanger/antenna structures for dual-functionality,
- Original IC-antenna co-integration techniques to address simultaneously the impedance matching, radiation pattern and thermal management requirements.

IV. Conclusion

Active cooling technologies in IC-integrated mm-wave phased arrays have been discussed. Dual-function elements have been revisited as a promising direction towards an energy efficient and low-profile antenna system. Two classes of heatsink antennas (i.e. 3D heatsink on top of a planar antenna and 3D antenna as a heatsink) have been reviewed with various examples from the literature. The existing approaches have been critically analyzed from the EM-thermal modeling, design and optimization perspectives, while considering the multidisciplinary demands of beyond-5G applications. Several future research lines have been established.

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