Evolutionary algorithms applied to multi-layered radiative cooling metamaterials

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Abstract **– A newly design method for designing multi-layered radiative cooling metamaterials based on evolutionary algorithms is exposed. The developed GA has been tested in three cases, resulting in three different structures that achieve, theoretically under direct sunlight, a net cooling power of 39.96 W/m^2, 57.78 W/m^2 and 61.77 W/m^2. Such devices are composed of 9, 15 and 24 layers respectively with a total thickness of less than 4.8 µm in the worst case. By the nature of the method, fewer design experience in metamaterials is needed, as well as it is free-cost, due to the use of analytical calculations for the emissivity of the metamaterials instead of a commercial generic electromagnetic solver. Automated design of radiative cooling multi-layered structures and other applications in the infrared range can be further developed with this work.**

I. INTRODUCTION

It is a fact that one of the current hardest challenges for society is climate change, with its well-known consequences [1]. This pressure leads towards the research of novel solutions able to obtain more neat energy and more recently, the reduction of the power demand. Current cooling systems such as air-conditioning in buildings show a poor efficiency. Moreover, global warming is increasing their demand, which is worsened by their high energy consumption, leading to a vicious circle which increasingly harms the environment each year.

In recent years, a solution has emerged under the name of radiative cooling [2]. Radiative cooling is a physical phenomenon that allows any body to lose heat in the form of electromagnetic waves radiated to space. It is a combination of two factors: the atmospheric window and the black body radiation. The former is a frequency band, between 8 and 13 µm mainly, in which the absorption and reflection of the atmosphere is very low, allowing the electromagnetic waves at these wavelengths to cross it freely. The latter explains that any body that is at some temperature above 0 K exhibits a radiation spectrum in a wide range of wavelengths. The peak of radiation as well as its magnitude shift with the object temperature and at ambient temperature takes place within the atmospheric window. These two facts allow a heath transfer between earth and space, which is much cooler and larger than earth, and hence is a great deposit for excess heath.

Radiative cooling has been researched recently, bringing a large amount of solutions that exploit the phenomenon such as polymers [3], paints [4], fabrics [5], structural materials [6] and metamaterials [7]. Metamaterials present the best performance among all, but they lack a defined design strategy and usually the manufacturing process is complicated. Thin-film multi-layered metamaterials stand out for having an easier manufacturing while maintaining the performance. In this article, we propose a design method for multi-layered structures for radiative cooling based on analytical calculation and genetic algorithms. Besides, it can be used for different applications in the infrared range.

II. STRUCTURE DESIGN

The key parameter in radiative cooling is the so-called net cooling power. It states in Watts per square meter the cooling capacity of a device. This value is computed according to Eq. (1):

$$P_{net}(T,T_{amb}) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{sun} - P_{loss} \quad (1)$$

where P_{rad} is the power radiated by the structure, P_{atm} is the energy received from the atmosphere, P_{sun} is the energy captured from the sun and P_{loss} is the heat loss associated with thermal convection and conduction with the surrounding environment. It is important to note that P_{net} is dependent on the device and ambient temperature, T and T_{amb} respectively. Ambient temperature is set to 300 K (26.85ºC) and the device temperature to 293 K (19.85ºC).

Maximum atmospheric emission, zero solar absorption and minimum heat loss is desired for daytime radiative cooling. Thermal losses are omitted in calculation for simplicity and the atmospheric transmittance has been computed for Navarra using [8]. To calculate P_{net} it is also necessary to know the emissivity of the structure. Kirchhoff's law of thermal radiation establishes that the emissivity and the absorptivity of a body are equal as long as it is in thermodynamic equilibrium. Then, the emissivity can be calculated applying Eq. (2).

$$\varepsilon(\lambda) = 1 - R(\lambda) - T(\lambda) \qquad (2)$$

where $\varepsilon(\lambda)$ is the emissivity, $R(\lambda)$ is the reflectance and $T(\lambda)$ is the transmittance, all wavelength dependent.

An analytical method for computing these values has been implemented in Python following the method presented in [9], with a computation wavelengths between 0.28-26 µm. It applies Snell's law to find $R(\lambda)$ and $T(\lambda)$ of a lossy thin-film multi-layered structure. The design has been done using a genetic algorithm (GA) with Python library DEAP [10]. Using natural selection axioms, the GA searches for the best solution in a set. In our case, we seek the highest net cooling power given the number of layers, their thicknesses and their corresponding materials. Three GAs have been executed with the parameters of Table I.

TABLE I

Parameters	***Population size***	***Descendants number***	***Crossover probability***	***Mutation probability***	***Recombination***	***Mutation***	***Selection***	***Codification***
Genetic algorithm	200	200	0.8	0.35	Mixture	Bit inversion	Tournament	Gray

Table 1. Parameters of the genetic algorithms

The three GAs consider a number of layers (N) equal to 10, 20 and 30, respectively. H_{max} is the maximum total height, which has been set to 5 µm; H_n is the thickness of each layer, which may take a value among 60 equally spaced values between 10 and 1000 nm for the first algorithm and between 10 and 300 nm for the rest. Note that if two adjacent layers are of the same material, they will be merged, thus, the number of layers in the final structure will be reduced. By consulting the literature, we have included in the GA different materials: SiO_2 (silicon dioxide), Al_2O_3 (aluminum oxide), MgF_2 (magnesium fluoride) and TiO_2 (titanium dioxide) as they have a good solar reflection and at the same time they present a good emissivity within the atmospheric window. Therefore, the material and thickness of each layer is coded with 2 and 6 bits respectively, obtaining a vector of length $8\times N$ bits for each individual of the GA. Each individual represents a solution for the whole metamaterial.

III. RESULTS

Fig. 1 depicts the GAs results. The maximum number of layers differ from the obtained real layers due to the merge of similar adjacent layer materials. Real layer numbers are 9, 15 and 24 with a total height of approximately 2.5 µm, 3.9 µm and 4.8 µm for simulations 1, 2 and 3. Such simulations have calculated 142,074, 132,274 and 191,103 solutions each respectively and interestingly, alumina has been discarded by the GA. Therefore, they are designed for homes and office buildings due to being set near the comfort temperature. The net cooling power under direct sunlight is 39.96 W/m^2, 57.78 W/m^2 and 61.77 W/m^2, respectively.

IV. CONCLUSIONS

Three multi-layered metamaterial structures for radiative cooling have been designed using genetic algorithms with a net cooling power under direct sunlight as high as 61.77 W/m^2. This is a novel way to design thin-film radiative coolers that can also be of interest for other infrared applications. Moreover, it also opens the door to the development of automatic design software for thin-film metamaterials. The main disadvantage is that the computational cost is proportional to the sample space, which is desired to be large for the best solution to be included. Trying to find a good starting point for the GA will improve greatly the results and the computation time or, inherently, the required hardware resources. In the future, prototype measurements will be done for checking the validity of this study.

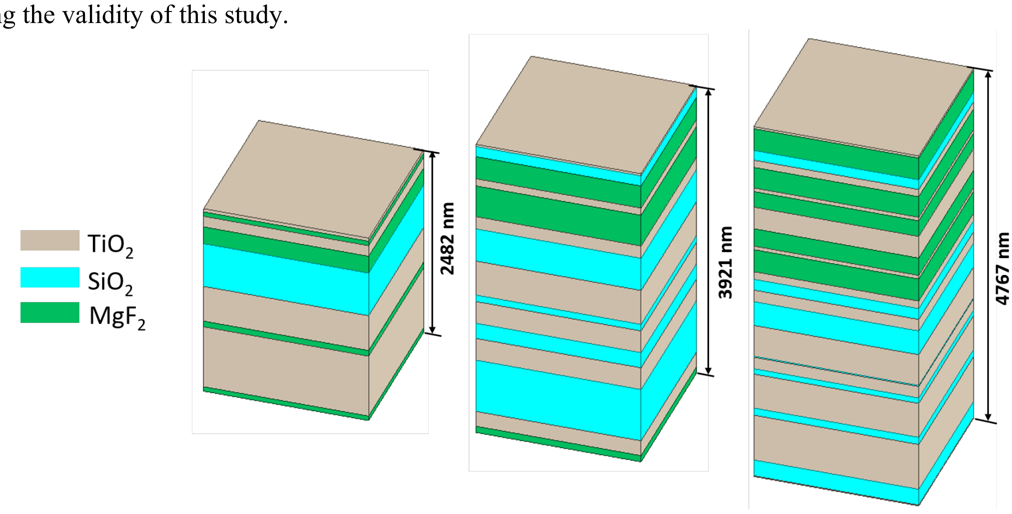

Fig. 1. Structures designed by the three genetic algorithms of 9, 15 and 24 layers respectively

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