# Design of multi-layered radiative cooling structures using evolutionary algorithms

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***Abstract*—In this work we present a novel way to design thin-film radiative cooling metamaterials based on genetic algorithms. Three simulations with different design constraints have been done, resulting in three structures that achieve 39.96 W/m$^2$, 57.78 W/m$^2$ and 61.77 W/m$^2$ under direct sunlight, respectively. These structures are shorter than 5 µm of height and are composed of 9, 15 and 24 layers. This design method has the advantages of being automatable, needs fewer design experience in metamaterials and does not rely on commercial simulators. This work opens the path to an easy way of automated design of thin-film multi-layered devices for radiative cooling and other applications in the infrared range.**

## I. Introduction

CLIMATE change is becoming more of a concern each year for society [1]. Its pressure has led towards the search of novel technologies for clean energy production as well as reducing the energy demand as much as possible. Among all consumption systems, cooling methods like air-conditioning in buildings stand out for being energetically inefficient. Furthermore, economical and energy cost of such systems are increasing due to global warming, which is aggravated by the energy production for them, making a vicious circle that is increasingly damaging the environment.

A solution has emerged under the name of radiative cooling [2], which is a physical phenomenon by which any terrestrial object losses heat in form of radiation that is sent to outer space. This process can be explained by the combination of black body radiation theory and the infrared atmospheric window. The former states that any object at some temperature above 0 K radiates energy at all wavelengths, with its radiation peak and spectral location modulated by its temperature. At ambient temperature this peak of radiation happens between 8-13µm, a band where the atmosphere is transparent to radiation (hence the name of atmospheric window), allowing waves at such frequencies to cross freely to outer space. Then, there is a direct heat transmission between earth and space, which is at 3 K and is infinitely large compared to earth, making a great storage for excess heat without wasting energy in the process.

Several devices exploiting radiative cooling have been proposed in recent years using different technologies. Paints [3], polymers [4], metamaterials [5], fabrics [6] and building materials [7] are just a few examples of such research. Among these options, thin-film multi-layered structures stand out for their performance and easier manufacturing compared to metamaterials, which bring the best performance but lack of a defined design strategy and ease of manufacture. In this work, we present a design method for thin-film radiative cooling devices based on the analytical calculation of the response and an optimization based on evolutionary algorithms. Obtained results will be checked in the future with a prototype and its measurements.

## II. Structure design

The most important parameter for radiative cooling devices is the net cooling power, which states the cooling capacity of a structure in Watts per square meter. Such value is calculated using 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, $P_{atm}$ the power absorbed from the atmosphere, $P_{sun}$ the power received from the sun and $P_{loss}$ are the thermal losses by convection and conduction phenomenon with the environment, $T$ is the temperature of the body and $T_{amb}$ is the ambient temperature.

Note that $P_{net}$ is a function of the temperature of the device ($T$) and of the ambient temperature ($T_{amb}$). Also, for daytime radiative cooling, total solar reflection is desired along with maximum atmospheric emission. The model of the atmospheric window has been calculated for the region of Navarra using [8]. Thermal losses have been omitted for simplicity. For calculating $P_{net}$, the emissivity in the atmospheric window and the absorptivity in the solar spectrum of the structure have the greatest impact on performance among the computed wavelengths (0.28-26 µm). By Kirchhoff's law of thermal radiation, emissivity and absorptivity are matched for an object in thermal equilibrium. So, the emissivity can be computed applying Eq. 2,

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

where $R(\lambda)$ is the reflectance and $T(\lambda)$ the transmittance, both dependent on wavelength λ.

Both $R$ and $T$ and hence the emissivity are calculated using the analytical method presented in [9] implemented in Python. It requires little computational effort compared to a general electromagnetic solver. Using Snell's law, it is possible to obtain both $R(\lambda)$ and $T(\lambda)$ of a generic lossy multi-layered structure.

The optimization of the structure is based on evolutionary algorithms, which are founded upon natural selection axioms. Specifically, a genetic algorithm (GA) has been used implemented with DEAP [10]. This algorithm tries to find the best solution among a set of possibilities; in this case, the best cooling power given certain materials, number of layers and their respective thicknesses. Three simulations have been designed with the parameters of Table I.

The three optimizations performed vary in the number of layers ($N$) considered: 10, 20 and 30 for simulations 1, 2 and 3 respectively. The maximum height of the structure ($h_{max}$) is 5 µm and the possible values of thickness for each layer ($h_n$) are 60 equally-spaced values between 10-1000 nm for the first simulation and between 10 and 300 nm for the latter two. Despite considering $N$ layers, the simulations actually account for structures with less layers if some material is repeated in adjacent layers.

TABLE I

| ***Parameters*** | ***Sim. 1*** |
|---|---|
| Population size | 200 |
| Descendents number | 200 |
| Crossover probability | 0,8 |
| Mutation probability | 0,35 |
| Recombination | Mixture |
| Mutation | Bit inversion |
| Selection | Tournament |

Table 1.Parameters of the genetic algorithms

Based on the literature, we have selected for our algorithm titanium dioxide ($TiO_2$), magnesium fluoride ($MgF_2$), aluminum oxide ($Al_2O_3$) and silicon dioxide ($SiO_2$) for the layer materials as they are good reflectors between 0.3-4µm, the solar spectrum, while presenting at the same time a considerable emissivity in the atmospheric window. Then, each layer is represented by a vector of 2 bits accounting for the material and 6 bits for the thickness, resulting in a vector of 8×$N$ bits length in gray codification for the whole metamaterial.

## III. RESULTS

The resulting multi-layered radiative cooling structures are presented in Fig. 1. Note that the number of layers differ from the maximum number of layers defined in the simulations. Considering the adjacent layer repetition as one unique layer, the number of respective combinations or solutions calculated by simulations 1, 2 and 3 are 142,074, 132,274 and 191,103.

The selected ambient temperature is $T_{amb}$ = 26.85ºC (300 K) and the device temperature is $T$ = 19.85ºC (293 K), which is near the comfort temperature. So, their performance will be expected for buildings, homes and offices. With those temperatures, the resulting devices achieve a net cooling power under direct sunlight of 39.96 W/m$^2$, 57.78 W/m$^2$ and 61.77 W/m$^2$. Note that this cooling power is normalized to the surface that is faced to the sky. Also, the height of the devices of Fig. 1 are approximately 2.48 µm, 3.92 µm and 4.77 µm, respectively.

## IV. CONCLUSIONS

We have reported a novel way to design thin-film multi-layered structures for radiative cooling and more broadly, for infrared applications. Using this method, we have designed three functional radiative cooling devices for daytime operation that achieve, in the best case, a net cooling power of as much as 61.77 W/m$^2$. Further research must be done in order to improve the performance of the algorithm in matter of time vs net cooling power achieved. This can be done by finding a good starting point so the solution set is more limited, which would open a tradeoff between design experience and time, or also essential, the need of computational power. Also, a prototype will be built and measured to check the validity of this study.

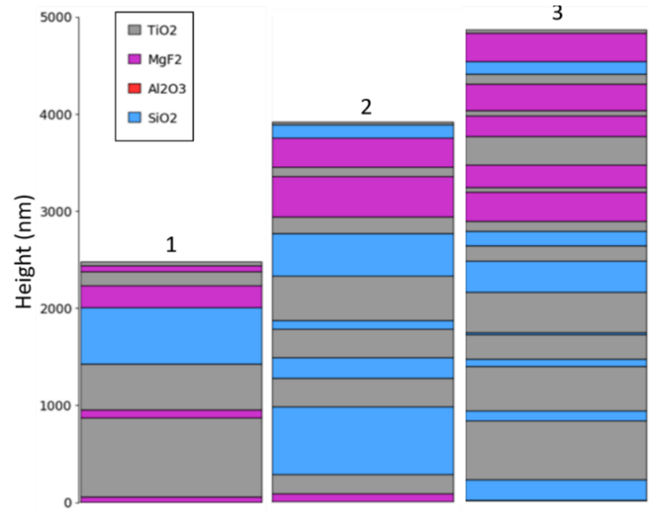


**Fig. 1.** Multi-layered radiative cooling structures found by each genetic algorithm. The first structure has actually 9 layers, the second 15 and the third 24.

## ACKNOWLEDGMENTS

This work has been done during the project "Algoritmos EVOlutivos aplicados a dispositivos de enfriamiento radiativo pasivo ultracompactos basados en METAsuperficies (AEVOMETA II), funded by the Government of Navarre.

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