Optimal design of reflecting photonic structures for space applications

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Summary. During atmospheric entries, vehicles can be exposed to strong electromagnetic radiation from gas in the shock layer. We propose and analyze silicon carbide and glassy carbon structures to increase the reflection of radiation. We performed numerical optimizations of photonic structures using an evolutionary strategy. Among the considered structures are layered, woodpile, porous and guided-mode resonance structures. The role of structural imperfections on the reflectivity is analyzed.

1 Introduction

Practical applications of photonic crystals (PhCs) are diverse [1, 2]. An interesting, but not yet practically realized, application of PhCs is as radiation shields for atmospheric re-entry of space vehicles. Electromagnetic radiation from ionized gas in the shock layer can constitute up to 30-50% [3] of the overall heat flux for lunar return trajectories, although for relatively short times. For Jupiter entries, on the other hand, most of the heating is radiative [4]. Therefore, in addition to protection against convective heating, a reentry thermal protection systems (TPS) should also be designed for radiation shielding. Ideally, the design should be tuned to the radiative spectra of a specific planet and specific entry conditions.

One of the easiest way to design radiation shields for atmospheric re-entry is with layered media [5]. Provided the two constituent materials possess a sufficient dielectric contrast and low absorption, broadband radiation shields with high omnidirectional reflection can be designed [6]. However, applications such as atmospheric re-entry impose many additional constraints on the material properties (thermal, mechanical, etc.). Therefore, finding a suitable pair of materials can be very demanding.

Currently, TPS for the most demanding atmospheric re-entries are made of highly porous carbon based materials. These materials, for example, PICA (phenolic-impregnated carbon ablators), possess many of the required thermal and mechanical properties. However, these materials are strong absorbers of radiation and therefore currently offer no protection at all from radiative heating. On the other hand, if these materials could be structured in such way that high reflection is obtained, radiative heating of the vehicle during re-entry could be reduced. We analyze the potential of glassy carbon and silicon carbide as radiation shields for Earth atmospheric re-entry. The effects of structural imperfections on reflectivity are also analyzed.

1.1 Optimization goal

The goal is to design a radiation shield that maximizes the total reflection of normally incident *unpolarized* radiation u_ν, shown in Fig. 1.

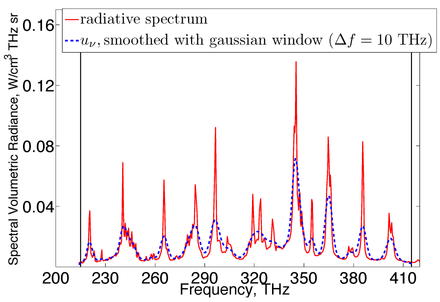

Fig. 1. (Red curve - experimental data of spectral radiation distribution, obtained at atmospheric re-entry relevant conditions [7] blue dashed curve - spectrum smoothed with Gaussian window function of full width $\Delta f = 10$ THz.

Therefore, the function to be maximized is:

$$\langle R_{u_\nu} \rangle = \frac{\int \mathrm{R}_\Sigma u_\nu d\nu}{\mathrm{u}_{\mathrm{tot}}}, \quad \mathrm{u}_{\mathrm{tot}} = \int u_\nu d\nu, \tag{1}$$

where R_Σ is the total reflection of the incident unpolarized radiation:

$$\mathrm{R}_\Sigma = 0.5(\mathrm{R}^\mathrm{s} + \mathrm{R}^\mathrm{p}), \tag{2}$$

where R^s and R^p are the sum of reflection efficiencies for the s- and p-polarization, respectively:

$$\mathrm{R}^{\mathrm{s,p}} = \mathrm{R}_0^{\mathrm{s,p}} + \sum \mathrm{D}_\mathrm{i}^{\mathrm{s,p}}, \; \mathrm{i} = \pm 1, \pm 2, \ldots \tag{3}$$

here the summation is performed over the propagating diffraction orders in the upper air half space.

For numerical optimization, we used evolutionary strategy (ES) algorithms. Based on previous experience [8], it is very powerful for real parameter optimization problems and outperforms genetic algorithm, particle swarm optimization, and other methods in most cases. We used an (m+n) evolutionary strategy with adaptive mutation for the optimization. Here m is the initial number of parents and n is the number of children created in each generation.

Some of the structures to be optimized are shown in Fig. 2.

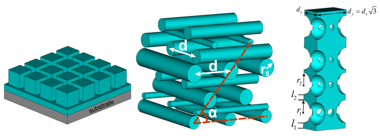

Fig. 2. (From left to right: guided mode resonance structure, woodpile, porous-reflector

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References

1. J. Joannopoulos, S. Johnson, J. Winn, and R. Meade, *Photonic crystals: molding the flow of light* (Princeton Univ Pr, 2008).
2. V. Shklover, L. Braginsky, G. Witz, M. Mishrikey, and C. Hafner, “High-Temperature Photonic Structures. Thermal Barrier Coatings, Infrared Sources and Other Applications,” Journal of Computational and Theoretical Nanoscience **5**, 862 (2008).
3. J. Grinstead, M. Wilder, J. Olejniczak, D. Bogdanoff, G. Allen, K. Dang, and M. Forrest, “Shock-heated Air Radiation Measurements at Lunar Return Conditions,” AIAA Paper **1244**, 2008 (2008).
4. C. Park, “Stagnation-region heating environment of the galileo probe,” Journal of thermophysics and heat transfer **23**, 417–424 (2009).
5. N. Komarevskiy, L. Braginsky, V. Shklover, C. Hafner, and J. Lawson, “Fast numerical methods for the design of layered photonic structures with rough interfaces,” Optics Express **19**, 5489–5499 (2011).
6. N. Komarevskiy, V. Shklover, L. Braginsky, C. Hafner, O. Fabrichnaya, S. White, and J. Lawson, “Design of reflective, photonic shields for atmospheric reentry,” Journal of Electromagnetic Analysis and Applications **3**, 228–237 (2011).
7. A. Brandis, C. Johnston, B. Cruden, D. Prabhu, and D. Bose, “Uncertainty analysis of neqair and hara predictions of air radiation measurements obtained in the east facility,” in “42nd AIAA Thermophysics Conference,” (American Institute of Aeronautics & Astronautics (AIAA), 2011).
8. J. Fröhlich, “Evolutionary optimization for computational electromagnetics,” Ph.D. thesis, ETH Zurich, IFH Laboratory (1997).