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Refractive sail and its applications in solar sailing

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ABSTRACT

Radiation pressure can be generated by interactions of electromagnetic (EM) waves with matter. Conventional in-space photonic propulsion systems like solar sails or solar photon thrusters operate by reflection of EM waves. This paper introduces a new type of solar sail which generates thrust by means of refraction of light through a thin film composed of micro-prisms. The main feature of the proposed refractive sail is its relatively large tangential radiation pressure, generated at near-normal radiation incidence. A method for computation of radiation pressure, by having the direction and power of input and output light beams, was introduced. Then a simple analytical approach for optimal design of the refractive film was presented, and ray tracing was utilized for computation of the radiation pressure to a good approximation. A refractive sail can be utilized in applications which a tangential force, especially at near-normal radiation incidence, is required. By utilizing this sail for orbit raising from low-Earth orbit (LEO), the minimum possible altitude for solar sailing can be reduced to about 500 km under the mean solar activity. Attitude control of solar sails along the sail's normal axis is another possible application of refractive films. Refractive films can also be utilized as solar collector (Fresnel lens) in space, which besides the convenience of their shape keeping, can be designed to be passively stable at the Sun-pointing attitude.

1. Introduction

Photon-propelled spacecraft including solar sails operate through exchange of energy and momentum with electromagnetic (EM) waves. This interaction between the matter and EM waves (photons) results in generation of radiation pressure. Radiation pressure was first described by Johannes Kepler as the cause of the observation in which comet tails always point away from the Sun. The physicist James Clerk Maxwell showed by his theory of electromagnetism that EM waves carry momentum and thus can apply force. The concept of utilizing radiation pressure (due to reflection) as a means of propulsion in space (solar sailing) was first proposed by Yakov Perelman, and then was presented as an engineering principle by Konstantin Tsiolkowsky along with Fridrikh Tsander [1]. The first detailed solar sail design was developed in the early 1980s by Jet Propulsion Laboratory for a rendezvous mission with Halley's Comet [2]. Since 2010 there have been several successful solar sailing missions including IKAROS [3], NanoSail-D2 [4], and LightSail [5] which proved the practicality of this technology.

Radiation pressure can be applied to a body through reflection, absorption, emission, diffraction, and refraction of the EM waves. A resultant force is applied to the sail due to the effect of radiation pressure on the irradiated surface of the sail. In 1970, Arthur Ashkin at Bell Laboratories showed that laser beams can apply a force to relatively transparent dielectric particles through refraction, and thus particles can be trapped and manipulated by light [6]. There have been several researchers who proposed utilizing the interaction of light with transmissive materials (including diffraction and refraction) as a means of propulsion in space. Swartzlander et al. predicted and experimentally verified the existence of a force in semi-cylindrical transparent rods. They discussed that the force is an optical analogue of aerodynamic lift and therefore called the refractive rods as 'lightfoil'. They also showed that these lightfoils can passively rotate to a stable attitude relative to the source [7]. They also proposed the possibility of using the micro rods with semicircular cross-sections as a means of space propulsion. Later, Swartzlander proposed using an array of active diffractive metamaterial elements with controllable diffraction angle to generate force which can be used as space propulsion [8]. Another research which proposed using transmissive elements as a part of propulsion system has been done by Matloff [9] who suggested using holographic coating underside of the solar photon thruster collector in order to increase the collector's focusing ability.

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Although a force can be applied to the matter through refraction of EM radiation, it's difficult to compute this force by analytical methods, due to the complex nature of such an interaction. The analysis and calculation of the force applied to refractive media due to radiation pressure, has been done by several researchers [10–13]. In practice, the force can be calculated by having the momentum of the incident and scattered light, which due to the complicated interactions of EM waves with media, is very hard to be achieved analytically. There are several numerical methods for computing the change in the momentum of the EM field or photons [13,14], which depend on the relative size of the particle (in this paper, the size of the smallest structural unit) and the wavelength of the light; in the case where the size of the particle is comparable to the wavelength of the light, computational electromagnetics methods [14] need to be applied to compute the changes of the momentum of the EM field, and where the size of the particle is much larger (more than ten times) than the wavelength of the light [15], the light can be considered as photons, and besides computational electromagnetics methods, geometrical optics (ray tracing) is also applicable [13].

In this paper, we propose a new kind of photonic propulsion generated by refraction of light in a thin film of micro-prism array which we call 'refractive sail'. The main feature of this new kind of sail is the large tangential radiation pressure at near-normal radiation incidence, which is nearly zero in the case of conventional sails. We introduce the method of computing the exerted radiation pressure on a media, by having the direction and power of the input and output light beams, which can be utilized to design the refractive sails or compute the generated radiation pressure. We also discuss some of the applications of these refractive films in the field of solar sailing and attitude control. This paper is organized as follows. In Sec. 2 the structure of the refractive sail is described, and the method and equations for computing the radiation pressure generated due to a wide range of light wavelengths are presented. This method can be applied by having the direction and power of the input and output light beams. The power and direction of the output beams can be computed by ray tracing or by a simple analytical method. Then the method of designing the geometrical properties of the micro-prisms is described. In Sec. 3 three applications of the refractive films in the field of solar sailing and attitude control are presented which include orbit raising from low-Earth orbit (LEO), attitude control along the sail's normal axis, and refractive solar collector (Fresnel lens) in space. Last, the conclusion was provided in Sec. 4.

2. Refractive sail and radiation pressure

The main idea behind the refractive sails is to deflect the light from its straight line to apply a momentum change in the EM field (light) and consequently in the media. Deflection of light beams can be applied by refraction through a transmissive material with a certain refractive index, or a gradient-index (GRIN) medium. GRIN materials can be designed to have a gradual variation of refractive index within the material. Therefore, it can be used to shape the path of the EM waves through the medium. Micro-scale GRIN structures can be fabricated using metamaterials [16–18]. In metamaterial regime, the analysis of the EM field and computation of the radiation pressure need to be done by computational electromagnetics to yield precise results. However, in this paper in order to simply introduce the idea of refractive sails, optical polymers with constant refractive indices are considered as the sail's material. The proposed refractive sail (film), as shown in Fig. 1, is composed of micro structures which are considered to be prismatic. However, any geometric shape which is able to refract the light beams in a specific direction within a certain range of incidence angles, can be used as the micro pattern of the sail. Micro-prism films are simple and can be fabricated using optical polymers by roll-to-roll technique [19–22]. When light beams pass through a boundary between two media with different refractive indices, a part of the light is reflected and the other part is refracted. The reflectivity and transmissivity of the boundary depend on the polarization of the light and given by Fresnel intensity equations [23]. The relationship between the incidence and refraction angles is described by Snell's law [23]. The change in the propagation direction of the EM waves caused by refraction, is considered to be the main source of the radiation pressure presented in this paper. By considering the very good transmissivity of optical polymers and the thin structure of refractive film (thickness of about 20 μm or more), the film has a negligible absorption which results in a negligible radiation pressure due to absorption. However, the reflection on the boundaries can affect the resultant radiation pressure which needs to be considered.

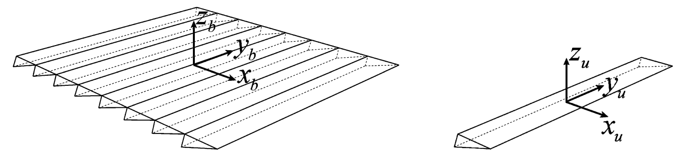

Fig. 1. Structure of the proposed refractive sail and the reference frames: (left) the total structure (micro-prisms are enlarged for visualization purpose) with the body-fixed frame, and (right) a micro-prism unit with the unit-fixed frame.

Throughout the paper we use two different reference frames, a unit-fixed frame, and a body-fixed frame. Every micro-prism unit (Fig. 1 right) has a unit-fixed frame attached to it denoted as $\mathcal{F}_u = \{O_u, x_u, y_u, z_u\}$, which its origin is located at the center of the flat surface of the prism, x_u points to the sharp side of the prism, z_u is outward on the flat surface of the prism, and y_u completes the right-handed reference frame. The body-fixed frame is a right-handed reference frame which is attached to the whole structure built by micro-prisms. Body-fixed frame is denoted as $\mathcal{F}_b = \{O_b, x_b, y_b, z_b\}$, which can be different for every structure constructed by micro-prisms. However, in the case of a refractive sail (Fig. 1 left), its origin is located at the center of the flat surface of the whole structure, x_b is in the direction of the sharp sides of the micro-prisms, z_b is outward on the flat surface of the structure, and y_b completes the right-handed reference frame. Throughout the paper, in the case of other structures constructed by micro-prisms, its body-fixed frame is shown in the respective figure of the structure. In the case of the refractive sail which is shown in Fig. 1 (left), the axes of the unit-fixed frames are along the axes of the body-fixed frame. In this paper, the vectors given in the unit-fixed and body-fixed frames, are defined by the subscripts u and b, respectively.

2.1. Computation of radiation pressure in a refractive material

The momentum $\vec{p}(\lambda)$ of a beam pulse with duration Δt and wavelength λ in vacuum, can be described by a magnitude which can be obtained by Einstein's mass–energy equivalence equation (by considering no rest mass), and a direction along Poynting vector (direction of energy flow) which can be given as

$$\vec{p}(\lambda) = \frac{W(\lambda)\Delta t}{c}\hat{k} \tag{1}$$

where $W(\lambda)$, c, and $\hat{k}$ are the spectral power of the pulse, speed of light in vacuum, and a unit vector in the direction of energy flow, respectively. The medium is considered as a system where $N_{i\,\max}$ light pulses enter it and $N_{o\,\max}$ pulses exit from it. The N_ith pulse enters the system along $\hat{k}_i^{N_i}$ with the spectral power of $W_i^{N_i}(\lambda)$, and the N_oth light pulse exits from the system along $\hat{k}_o^{N_o}$ with the

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