Spin of Microwave Propelled Sails

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Abstract. It is not widely recognized that a circularly polarized electromagnetic wave impinging upon a sail from below can spin as well as propel. Our experiments show the effect is efficient and occurs at practical microwave powers. The wave angular momentum acts to produce a torque through an effective moment arm of a wavelength, so longer wavelengths are more efficient in producing spin, which rules out lasers. A variety of conducting sail shapes can be spun if they are not figures of revolution. Spin can stabilize the sail against the drift and yaw, which can cause loss of beam-riding. So, if the sail gets off-center of the beam, it can be stabilized against lateral movement by a concave shape on the beam side. This effect can be used to stabilize sails in flight and to unfurl such sails in space.

SPIN DRIVEN BY CIRCULARLY POLARIZED ELECTROMAGNETIC WAVES

Circularly polarized electromagnetic fields carry both energy and angular momentum. A polarized electromagnetic wave impinging upon a sail can spin a sail For a sail in space, this effect allows 'hands-off' deployment and control of the sail spin at a distance.

Some theory has treated wave angular momentum coupling to objects. (See references 1-6.) The wave angular momentum L acts to produce a torque through an effective moment arm of a wavelength, so $L = N \nabla k \lambda$, with N the photon number. The wave energy is $E = N \nabla \omega$, so the ratio of L/E imparted by a wave is $L/E = 1/\omega$. Therefore, longer wavelengths are more efficient in producing spin. *This effect also allows unfurling of sails by driving spin-up.*

With an eye toward eventual deployment in orbit, we study unfolding of sails by spinning them up. The wave angular momentum imparted to the sail scales as λ/D, $L/L_Z = \lambda/D$, where D is the transverse scale of the power beam, which will be close to the sail size for efficient propulsion. This arises because a wave focused to a finite lateral size D generates a component of electric field along the direction of

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propagation of magnitude (λ/D) times the transverse electric field, as long as D exceeds the wavelength. So a sail beginning at small diameter can be spun open with an electromagnetic wave of wavelength a fraction of the beginning diameter. (Torque = wavelength × thrust, so wavelength on the order of the sail diameter should give maximum torque.) The spin S of a sail with moment of inertia I grows according to

$$\frac{dS}{dt} = \frac{2P(t)}{I}\frac{\alpha}{\omega}.$$

where P is the power intercepted by the sail. As the sail deploys, a shift to longer wavelengths could maintain the efficiency of transfer.

Clearly, there will be spin if the sail is an absorber of microwaves, $\alpha > 0$. This has been demonstrated for C-C microtruss sails by our team (Reference 5), and is explored further in the experiments described below.

Axisymmetric perfect conductors, for which $\alpha > 0$, cannot absorb or radiate angular momentum when illuminated. However, any asymmetry allows absorption. We have investigated the conditions under which a circularly polarized wave field transfers angular momentum to a macroscopic object, using exact electromagnetic wave theory. (See the Appendix for a discussion of the theory.) A rigorous solution of the boundary value problem for reflection from a perfectly conducting infinite wedge shows that waves convey angular momentum at the edges of asymmetries. Such absorption or radiation depends solely on the specific geometry of the conductor. We term this “*geometric absorption*“. Conductors can also radiate angular momentum, so their geometric absorption coefficient for angular momentum can be negative! The geometric absorption coefficient can be as high as 5, much larger than typical simple material absorption coefficients, which are ~1 to 0.1 for absorbers and ~ 0 for conductors. In the appendix, we apply the theory results to recent experiments which spun roof-shaped aluminum sheets with polarized microwave beams (Reference 5). Below we describe tests of such techniques for spinning the sail on a thread suspended in the laboratory frame. The variables explored are various shapes (discs, ‘roofs’, strips) with ‘cuts’ which are chosen to optimally interrupt currents on the sail surface to produce maximized absorption.

To use this effect to spin objects in space, both a circularly polarized microwave beam and a local weak transient gas ‘atmosphere ‘ would be required. This means producing a gas density with a mean free path of a tenth of the sail size or less. At ~100 km altitude, this would demand only 0.1 gm/s of gas, for 10 m sails. For spin-up taking minutes, only a few tens of grams are needed. A full discussion of our results is in Ref. 7, available on request.

SPIN EXPERIMENTS—APPARATUS AND MATERIALS

A schematic of the experiment is in Fig.1. The major systems are: High power microwave generation system; Microwave waveguide connection assembly and input into the experimental chamber; experimental chamber with sail-propeller support system; sail or propeller; vacuum and data acquisition system.

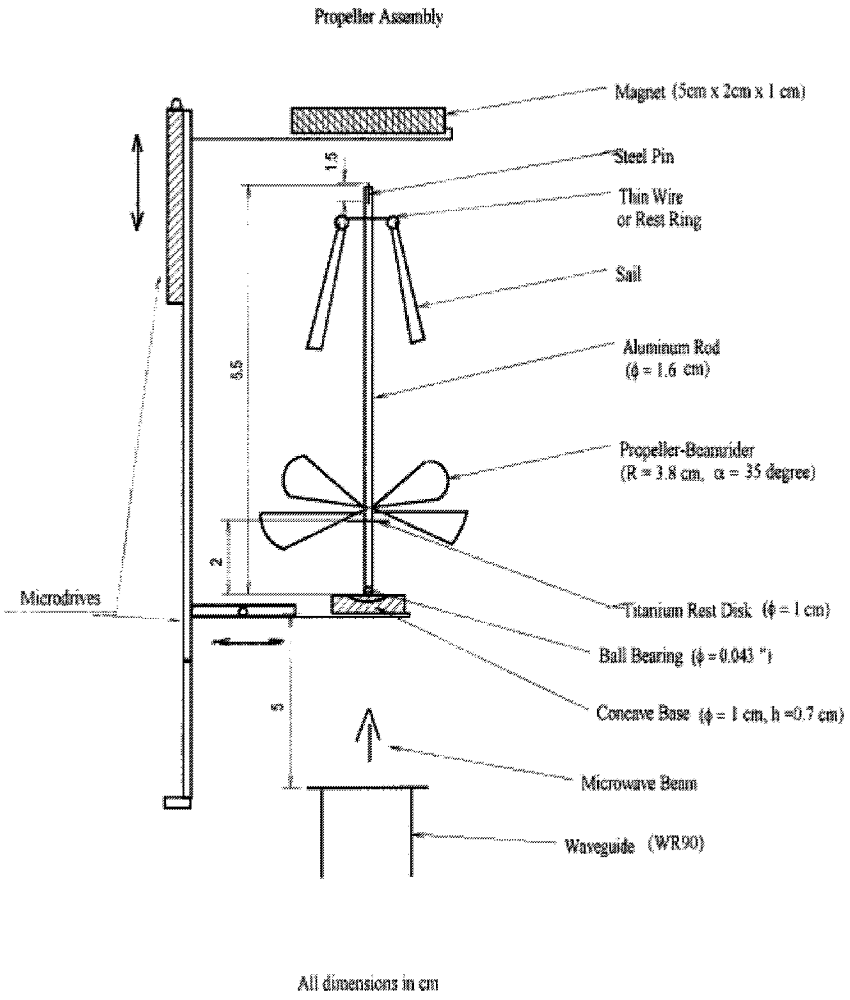

FIGURE 1. This is the Style for Figure Captions. Center this text if it doesn't run for more than one line.

The microwave power source is a CW klystron amplifier (Varian VA-864) with maximum power of 10 kW at 10.6 GHz. The klystron has a 17 kV power supply and water cooling system (8 gal/min) with heat exchanger and water pump. The waveguide assembly is built using WR90 waveguide and waveguide components in X-band (23mm x 10 mm). All the flanges of the waveguide connections are sealed with copper tape. In our first experiments we used the open end of a waveguide with flange as a microwave input in the experimental chamber. A high power microwave pressure window manufactured by CPI (Communication and Power Industries) was used for atmosphere - vacuum separation. The output microwave power was measured using a directional coupler (-60 dB) and thermistor power meter (model 432A) manufactured by Hewlett Packard Co. The experiments were conducted at power levels up to 2300 W. In order to get 10 kW of output power it is necessary to increase the input power up to 180 mW, given the gain coefficient of the klystron.

The idea here is to use a lift force provided by a magnetic field to offset the gravitational force and thereby reduce the total normal force necessary to support the sail assembly. In this case, the torque due to the frictional force at the base of the rod will be significantly reduced and less microwave power will be needed to spin. The rod holding the sail was placed on a special base, described below. The rod was supported vertically by the magnetic field of the permanent magnet, which was placed on supports above the sail. For the microwave spin experiments we used sails made of carbon fiber material manufactured by Energy Science Laboratories. In particular, we used a C—C microtruss cone with areal mass density 19.6 g/m^2. For the conductor experiments we used common aluminum foil with areal mass density of 30 g/m^2.

SPIN EXPERIMENTS—RESULTS

In our experiments, we used two types of microwave radiation: the linear polarized wave of TE_{10} mode radiated from the open end of the waveguide, and a circular polarized wave of TE_{11} mode radiated from the circular waveguide or horn.

A polarized electromagnetic wave impinging upon a sail can spin it. We studied spin of sails by photon geometric absorption, investigating the effect of shape and ‘cuts’ in the basic form to influence current patterns on the sail of different geometrical forms like a cone, roof, strip, and square. For some experiments the sail was specially cut at the edge to study the effect of interruption of the induced currents on the sail spin. The sail was suspended in the vacuum chamber on a carbon fiber thread or on a kevlar fiber thread

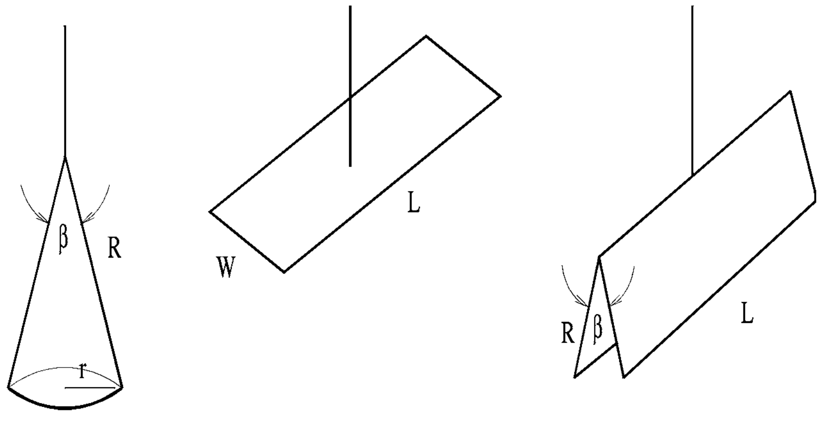

FIGURE 2. Sails shapes studies with circular polarization: cone, strip, and roof shapes.

The fiber thread was attached to the sail using high vacuum epoxy (Torr seal, Mechanical Laboratories Inc.). The carbon fiber was very difficult to handle due to its extreme fragility and stiffness. Each sail and its attached fiber were used only once and repositioning was difficult. Bringing the chamber up to atmospheric pressure completely destroyed the sail–carbon fiber connection. Kevlar fiber thread is much easier to work with, it is more flexible, strong and not as brittle as the carbon fiber. The sail-Kevlar fiber connection 'survived' several experiments. The sail was mounted so that it was centered with respect to the peak of the microwave power distribution and normal to the microwave beam. We tried to handle the sail material carefully to avoid possible surface contamination. Some experiments were performed with the support system described above. Each sail was irradiated by the microwave beam from below and spun in the direction of the wave polarization. The spin direction reversed if the direction of beam polarization was reversed. We studied sails made of different materials including carbon fiber material (carbon-carbon microtruss) (Energy Science Laboratory Inc., CA), aluminum foil and aluminum coated Kapton (courtesy of ORCON Corp., CA). Most of the experiments were performed with aluminum foil sails. All experiments were conducted in the evacuated chamber under vacuum conditions of 2 to 5 × 10^{-5} Torr to avoid the thermo-molecular effects described above.

We used the following model of rotational motion of the sail in order to estimate quantitatively the angular momentum transfer. We assume that only reflection takes place and no absorption of the microwaves by the sail material occurs, a very good assumption for aluminum.

$$I\frac{\partial^2\theta}{\partial t^2} = T_{thread} + T_{rf} + T_{damping} \ .$$

$$T_{thread} = -k_\theta \theta \ ; \quad T_{damping} = -\nu\frac{\partial\theta}{\partial t}, \quad T_{rf} = \alpha\left(\frac{P_s}{c}\right)\left(\frac{\lambda}{\pi}\right).$$

where I is the moment of inertia of the sail, T_{thread} is the restoring torque of the fiber, T_{rf} is the torque due to microwaves, $T_{damping}$ is the damping torque, k_θ is the torsional spring constant, ν is the damping constant, α is the coupling coefficient relating the microwave power on the sail, P_s to the applied torque, c is speed of light, and λ is the wavelength of microwave beam. At a certain total power of the beam P_t and respectively, power on the sail P_s, the sail will rotate to a maximum angle θ_m. Then the coupling coefficient is

$$\alpha = \left(\frac{2\pi}{\tau}\right)^2\left(\frac{\theta_m}{P_s}\right)\left(\frac{cI\pi}{\lambda}\right).$$

We define the efficiency coefficient as the total use of all beam power, including that power which misses the sail entirely.

$$\varepsilon = \alpha\left(\frac{P_s}{P_t}\right) = \left(\frac{2\pi}{\tau}\right)^2\left(\frac{\theta_m}{P_t}\right)\left(\frac{cI\pi}{\lambda}\right).$$

This coefficient gives the efficiency of using the total beam power to spin the sail.

Aluminum Strip Sail Tests

Strip sails made of aluminum foil (areal density $\sigma = 3$ mg/cm^2, sail length $L >> $ sail width w) were investigated. The maximum angle of displacement, θ_m, from the initial position of the sail was determined experimentally for each power level of the microwave beam P_t. The rotation of the sail was recorded by a video camera and then displayed on a TV screen. The angle of displacement for each power level was determined through measurement of the projection of the strip on the screen. The microwave power intercepted by the sail P_s was calculated for each particular case, accounting for sail size and its position with respect to the horn. After power was turned off the period of oscillations of the sail τ was measured. We determined the value of the coupling coefficient α using the above equation. The coupling coefficient α and efficiency coefficient ε are shown to an accuracy within 20% or less.

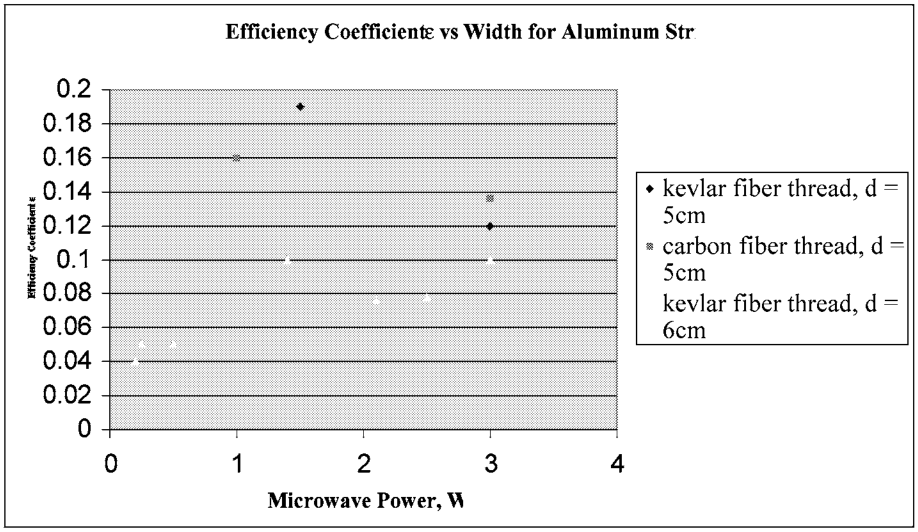

FIGURE 3. Coupling coefficient α vs. width of the strip for various horn distances.

A Scaling Rule for Coupling to Conducting Strips

We conducted our experiments on the microwave angular momentum transfer using aluminum shapes hanging from thin fibers of carbon or Teflon. The coupling coefficient between the beam and the sail was often quite high, ~1.

How can α exceed unity? A geometric argument may explain this. We know from theory that angular momentum is conveyed at the *edges* of conductors. As a wave diffracts around a conducting sail it is affected to a distance ~ λ laterally away from the sail. The diffraction pattern we observed (bright spots on the hanging thread, spaced about a wavelength apart) implies that wave energy within an area *larger than the sail area dL* (with L the length) can convey angular momentum. This is because the wave is disturbed over the distance λ, so the apparent area dL is in fact larger by a factor ~ $(1+2\lambda/w)$, taking into account the diffraction of the wave at the edges, where w is the width of the strip. We define the adjusted coupling coefficient α_1 as

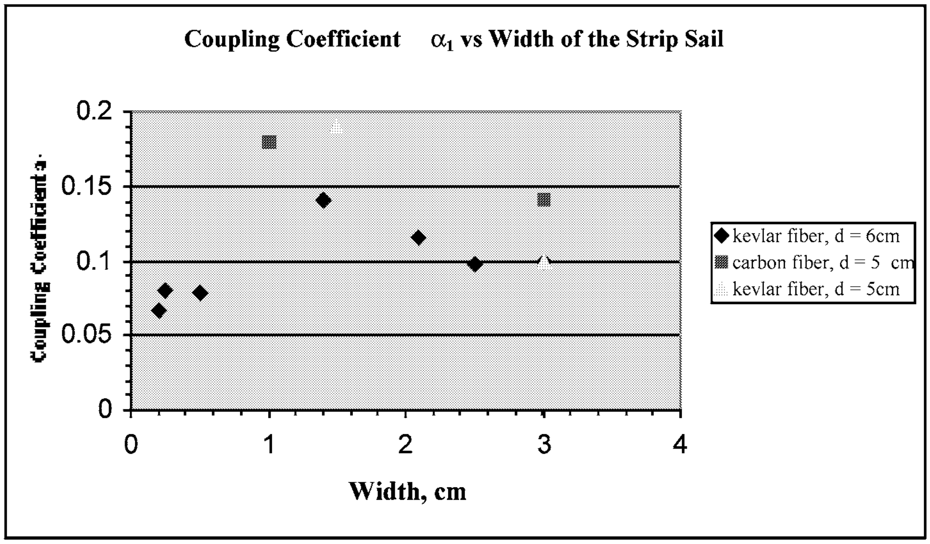

FIGURE 4. Efficiency coefficient ε vs. width of the strip.

$$\alpha_1 = \frac{\alpha}{1+2\lambda/w}.$$

where α is the experimental coupling coefficient. Fig. 5 shows enhanced coupling, so includes the wave energy conveying torque beyond the edge of the strip. This produces a peak between 1 and 2 cm, or about half a wavelength.

In order to investigate the effect of cuts in the sail surface, which can interrupt surface current patterns, on the beam–sail interaction, we conducted several experiments with strips that were slotted along the width or along the length of the strip.

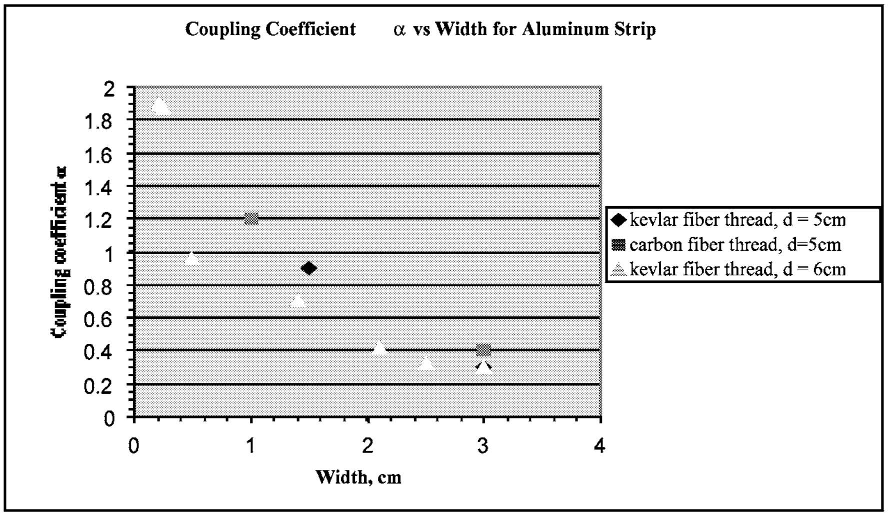

FIGURE 5. Coupling coefficient α_l vs. width of the strip.

TABLE 1. Coupling coefficient for aluminum strip sails with and without cuts.

Strip (Al foil)	Moment of Inertia, kg×cm^2	Coupling Coefficient
3 cm × 8 cm, without cuts	4.38×10^{-8}	0.3
3 cm × 8 cm, 2 cuts longitudinal (2.5 cm each)	4.38×10^{-8}	1.1
3 cm × 8 cm, 6 cuts transverse (1 cm each)	4.38×10^{-8}	0.68

The transfer of angular momentum from the microwave beam to the strip sail depends on the width of the strip and its relative size with respect to the wavelength of the beam. The smaller the width the higher is the coupling coefficient. However, the efficiency of using the beam power decreases with smaller width and has a maximum for a strip with width equal to about half the wavelength. Slotting the strip sail leads to an increase of the coupling coefficient. The increase depends on the size of the cut, the number of cuts and the spacing of the cuts. See Table 2 for some examples.

<u>Aluminum square sail tests.</u> Some tests were conducted with sails square in shape. The results of the experiments are in Table 2. In this case slotting the sail decreased the coupling coefficient and the smaller sail has a higher coefficient.

TABLE 2. **Coupling coefficient for aluminum s square ails with and without cuts.**

Strip (Al foil)	Moment of Inertia, kg×cm^2	Coupling Coefficient
3 cm × 3 cm, without cuts	4×10^{-9}	0.21
3 cm × 3 cm, 4 cuts (1.5 cm each)	4×10^{-9}	0.07
1.25 cm × 1.25 cm, without cuts	1.2×10^{-10}	0.54

<u>Aluminum roof-shaped sail tests.</u> We investigated aluminum foil sails in the form of a roof. Experiments were conducted for a 'long' (*L*= 6 cm) roof and for a short roof (*L* = 3.4 cm). We tried to determine the dependence of the coupling coefficient for the roof sail on its opening angle. This will determine the effect of multiple reflections within the roof.

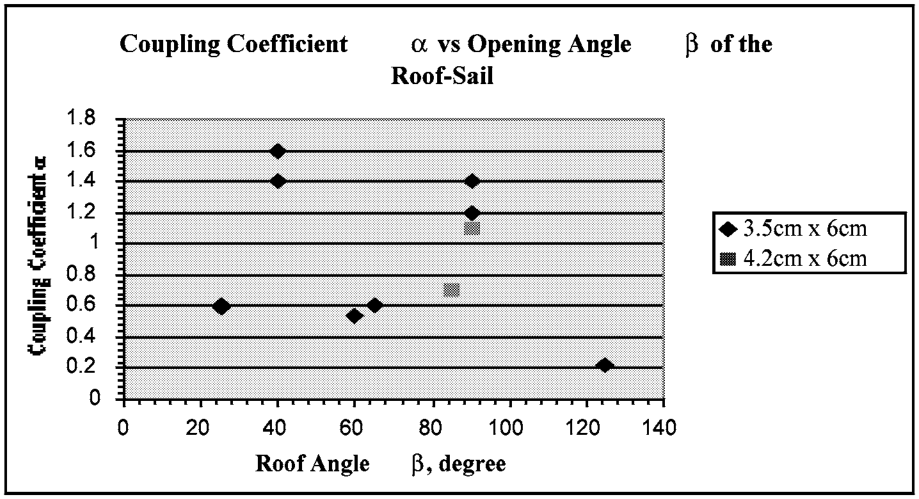

FIGURE 6. Coupling coefficient α vs. opening angle β of roof-shaped sails.

It is interesting to note that for the small roof (1.5cm × 3cm) with an opening angle of 2° the coupling coefficient is very high and equals 29, which is almost 30 times larger than the coupling coefficient for the roof with an opening angle of 90°. It seems that the behavior of the aluminum roof sail is similar to the behavior of a strip sail that has a size equal to the base of the roof sail. Apparently, for these geometries internal reflection (the influence of the opening angle) does not play a significant role in the sail dynamics.

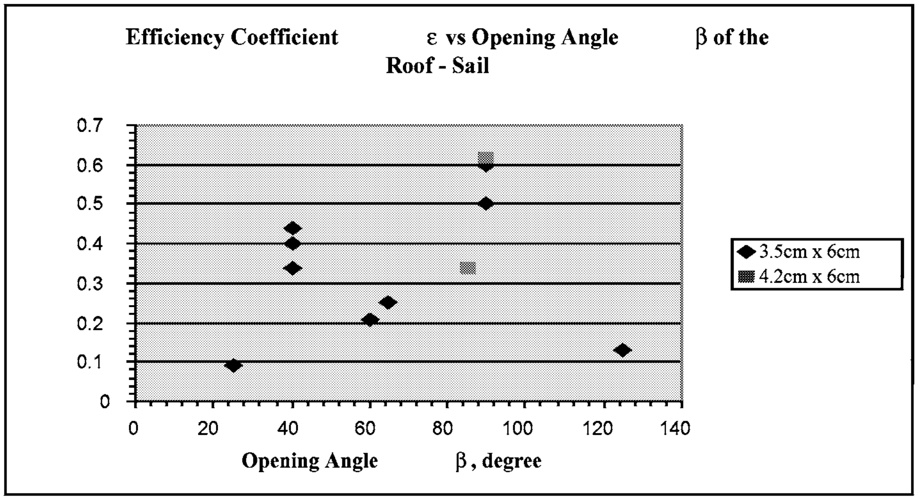

FIGURE 7. Total efficiency $\varepsilon = \alpha(P_s/P_t)$, which measures the total use of all beam power, including that which misses the sail entirely.

The plot above shows the total efficiency ε of beam power use, vs. roof angle. This efficiency we define as $\varepsilon = \alpha(P_s/P_t)$. This measures the total use of all beam power, including that power which misses the sail entirely. For a real system, this is an important design element. The two peaks occur where the roof width at its base is λ (120 degrees) or $\lambda/2$ (50 degrees*). This implies a cavity-like resonance effect for the roof.*

Results for the larger and long roofs (r = 3.5cm, L = 6 cm) have prominent maxima so the refractive effects are more expressed (the ratio of the roof height to the wavelength is important and the ratio of the width of the roof base to the wavelength is important also). The maxima correspond to the roof angles 40° and 90°, where the roof at its base is λ or the height of the roof is λ (within 20%). Clearly there are diffraction and reflection effects and it looks like they could be 'competitive ' for certain cases. For example, concerning the shorter roof (3.5cm x 3cm), the plot for the coupling coefficient is similar to the one for the strip sail. *It seems that the diffraction of the wave by the short roof (L = 3cm) overshadows the reflective effects due to the roof angle (height of the roof) and the roof sail 'behaves' as a strip sail.*

Carbon cone sail test

The carbon fiber material (carbon-carbon microtruss) cone should spin under the influence of a polarized microwave beam, due to both absorption of the microwaves by the carbon fiber material and to the geometric absorptivity, if it is not symmetric. The experiment was conducted with a carbon cone (a conical beamrider, JPL PO#1212552, mass is 0.056g) hanging on a kevlar fiber thread. The cone base had a radius R = 2.4 cm and a cone angle of 90°. The cone was placed at a distance of 5.5

cm from the horn of the polarizer. When the cone was irradiated with the polarized microwave beam, it rotated in the direction of the wave polarization.

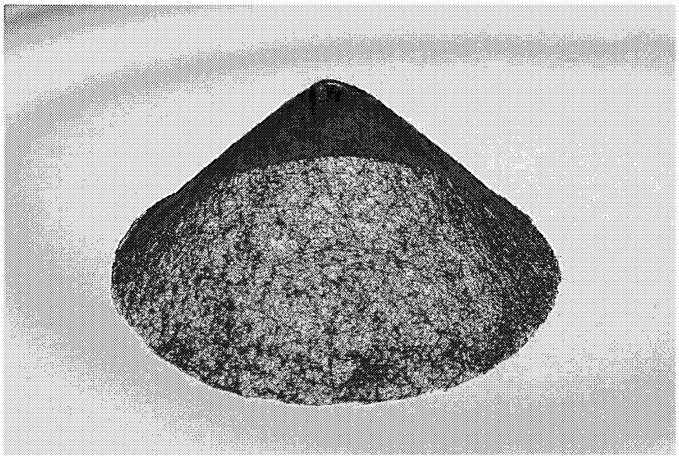

FIGURE 8 Conical sail-beamrider made of carbon fiber material.

Taking parameters of the motion from the linear regime, we can determine the coupling coefficient for the carbon cone. For example, given that the moment of inertia of the cone is $I_c = 1.6 \times 10^{-8}$ kg cm^2 and the maximum displacement angle is $\Theta_m = 50^\circ$ at beam power $P_t = 50$ W ($P_s = 15.3$ W) and the period of oscillation without microwave power is $\tau = 107$ s, the calculated coupling coefficient $\alpha = 0.1$. Since the measured absorptivity of the carbon material in the microwave is 10%, the rotation is due to simple absorption of the microwaves by the carbon fiber material. *This agreement checks our basic* picture.

We conducted many tests with cone sails made of *aluminum* foil. Theory shows that completely symmetrical objects (bodies of revolution) should not spin when irradiated by circularly polarized wave. *We did not observe any movement when we increased the beam* power *up to 1100 W, confirming that symmetric objects cannot be spun.* For a given cone, an areal cut does not significantly increase the coupling coefficient, even if it significantly destroys the shape and consequently the symmetry of the sail. But several cuts (just slotting the surface) will increase the coupling by a factor >10.

CONCLUSIONS

We conducted experiments demonstrating that a sail could be induced to spin when irradiated by a circularly polarized microwave beam. The sails spun due to transfer of the angular momentum of the incident microwave beam to the sail. The sails were suspended on either a carbon fiber thread or on a kevlar fiber thread. Spin properties were investigated as a function of the microwave power. We studied sails of different shapes and materials and calculated the coupling coefficient for each shape of sail. Our principal results

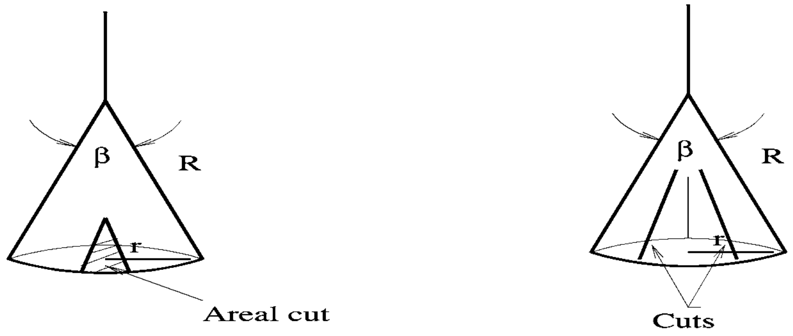

FIGURE 9. Types of cuts: Conical sails with an areal cut (left) and thin cuts (right). We find that the two cut types give very different couplings to circularized microwaves.

- As expected, a carbon fiber material cone spun under the influence of a polarized microwave beam with a measured coupling coefficient of 0.1, fitting independent measurements of carbon material absorption for microwaves in this frequency region.
- Coupling to conductors can be greatly enhanced, giving coupling coefficients of 1 or more, by the 'geometric absorption' effect (see Appendix), a previously unnoticed phenomena in classical electromagnetics.
- Transfer of angular momentum from the microwave beam to a strip sail depends on the width of the strip and its relative size with respect to the wavelength of the beam. The efficiency of using the beam power decreases with smaller width and has a maximum for a strip with width equal to about half the wavelength.
- *Slotting the strip sail leads to an increase of the coupling coefficient.* The behavior of the aluminum roof sail (of the size we studied) is similar to the behavior of a strip sail that has a size equal to the base of the roof sail.
- Slotting an aluminum cone sail can also significantly increase the coupling.
- Our experiments suggest strongly that cuts in good conductors (e.g., aluminum) constrain the circulating currents within it to the scale between the cuts. When this size is roughly a wavelength, maximum coupling occurs. Radial cuts give more coupling than azimuthal cuts.

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