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Levitation using microwave-induced plasmas

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The levitation of objects above a microwave horn is demonstrated. High-power microwave pulses generate a low-temperature, diffuse plasma on the surface of the horn window. The thermal effect of the surface plasma brings about a localized increase in the pressure and results in a vertical flow of air, thus levitating the object. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1887837]

Levitation is the act of lifting, suspending, or causing an object to move in air in seeming defiance of gravitation. Much work has been done on magnetic levitation, both ferromagnetic and diamagnetic, and some major applications have emerged.[1,2] A concept for microwave levitation was proposed by Askaryan *et al.*[3] and microwave plasmas were employed to demonstrate turbine and piston devices.[4] Recently, microwave cavity resonators have been studied as a way of overcoming friction in micromachines and microactuators.[5] Beamed microwave power has also been proposed[6–9] as a method of propulsion for space access. The present paper describes the levitation of objects using self-sustained microwave plasmas that generate localized increases in pressure. The work was inspired by lateral force (lifting) experiments carried out by Khodataev and coworkers at the Moscow Radiotechnical Institute.[10] In the experiments of Ref. 10, a small model was outfitted with a half-dipole "initiator" and suspended in a Mach 2 flow. *S*-band microwaves were incident on the model and were in resonance with the initiator. Upon absorbing the microwave power, the sharpened end of the initiator generated a small, hot plasma that resulted in the lifting force on the model.

Figure 1 is a schematic sketch of the present experimental setup to levitate objects using a low temperature, diffuse plasma on the surface of the horn window. Microwaves at 9.5 GHz (*X*-band) are fed to the microwave horn. The system provides pulses of 3 μs duration with a peak power of 210 kW (0.63 J/pulse). The pulse rate is typically 500 pulses/s, which provides an average power of 315 W. The microwave horn has a rectangular aperture 5.94 $\times$ 7.84 cm that is sealed by an alumina window of thickness 5.1 mm for maximum transmission at 9.5 GHz. The horn and waveguide are pressurized to 1 atm in order to inhibit breakdown within the waveguide. The horn is housed in an aerodynamic model (without the radioactive source) originally designed for testing in a Mach 6 flow.[11] The model is aligned vertically here and housed in an evacuable glass chamber. A metal box encloses the entire apparatus with several windows for viewing. The windows are covered with copper screen wire for safety. A 320 $\times$ 240 pixel CCD camera with a 10 Hz frame rate is employed to view the levitated objects.

At low pressures of air (<50 Torr), a diffuse surface plasma is generated on the alumina window. The plasma brings about a local increase in the pressure and results in a vertical flow of air above the window. This flow is used to levitate objects. A wooden frame is employed to suspend a vertical nylon thread in order to guide the object and prevent it from being ejected from the apparatus. For this purpose, a small hole is drilled in the center of each object. Figure 2 shows four frames depicting the levitation of a flat Styrofoam® disk at 11 Torr. The disk is 4.9 cm in diameter by 4 mm thick and weighs 0.18 g. Figure 2(a) shows the disk resting on the framework about 1 cm above the window prior to turning on the microwaves. Figure 2(b) was taken just as the microwaves are turned on (t=0 s) and shows the disk being thrust upward. Note the colored plasma at the bottom of the rig. In Fig. 2(c) (t=7.8 s), the disk has attained a somewhat stable horizontal attitude approximately 3 cm above the window. In Fig. 2(d) (t=10.2 s), the horizontal attitude is still holding. After 14 s, the microwaves are turned off and the disk falls back to the original position. The Styrofoam® disk was also tested without the wooden framework to see if the framework influenced the microwave output from the horn. In this case, the disk rose to a height of about 15 cm before being ejected, far above the height

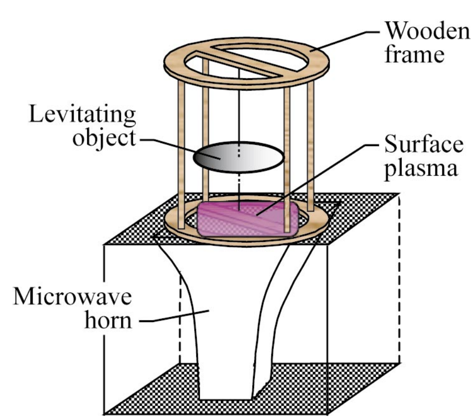

FIG. 1. (Color) Sketch of the microwave levitation apparatus.

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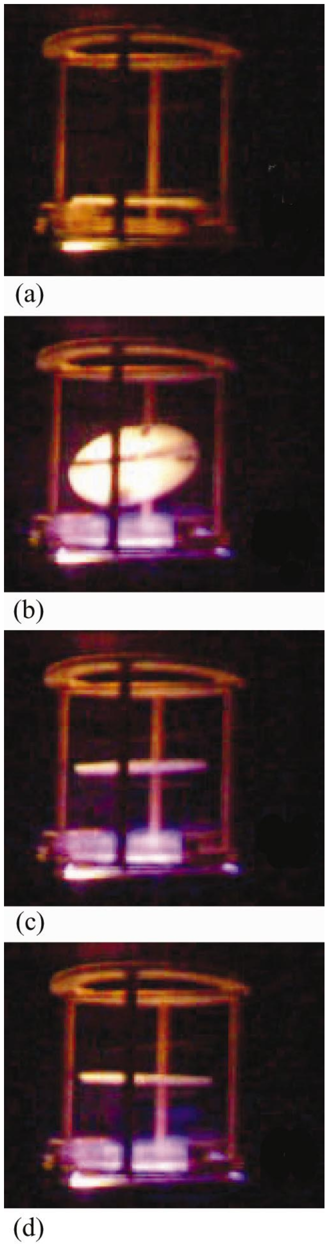

FIG. 2. (Color) Levitation of a Styrofoam® disk: (a) microwave off; (b) (t=0 s) microwaves turned on and disk thrust upward; (c) (t=7.8 s) disk stable; (d) (t=10.2 s) disk remains stable.

achieved when the wooden framework was employed. Several objects with vanes have also been levitated using the nylon guide thread in the wooden frame and have exhibited rotation. Future tests may be able to take advantage of rotation to stabilize freely levitated objects.

In the tests described above, the air pressure is low and diffuse plasma is formed on the window of the microwave horn. It is also possible to attain levitation at higher pressures by employing resonant initiators, as was done earlier.[10] A half-dipole initiator is typically a metal rod or wire attached to or embedded in the surface and whose length is approximately one half the microwave wavelength. For a microwave frequency of 9.5 GHz, this length is 1.58 cm. An initiator with sharply pointed ends increases the electric field in the vicinity of the tips and is capable of generating plasmas at higher pressures. In an alternate plasma excitation mode, nine initiators were embedded in the surface of a 6.3 mm thick Teflon® cap that covered the microwave horn. The initiators produced small, hot plasmas at their tips that enhanced the lift. In this configuration, the Styrofoam® disk exhibited levitation at pressures up to 1 atm. It may also be possible to obtain levitation by attaching initiators to the surface of the disk itself.

The nylon thread stabilizes the microwave levitation demonstrated in Fig. 2. A truly stand-alone levitation would require a local minimum in the elevating force. For microwave surface plasmas, it may be possible to alter the radiation pattern emanating from the horn in order to generate a torus shaped plasma. This would most likely result in a localized minimum in the elevating force. Employing the Bernoulli principle would then complete the scheme. Many other configurations of low-pressure diffuse plasmas or initiator-generated plasmas can be envisioned. These would all have the capability of providing mechanical motion in controlled environments.

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