Magnetron Coupling to Sulfur Plasma Bulb

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***Abstract*—Sulfur plasma lamps are a convenient, table-top system for the study of acoustics in dense, weakly ionized plasmas. Herein we describe the construction and tuning of a passive waveguide circuit capable of igniting and sustaining the sulfur plasma and exciting acoustic modes within it.**

Sulfur plasma lamps were developed as efficient, high-power light sources for use in large, open spaces [1, 2] and their broad, sun-like emission spectrum makes them attractive as light sources for solar-cell calibration [3, 4] and indoor horticulture [5, 6]. The bulbs for these lamps are typically 34 mm diameter and contain ~ 30 mg of sulfur powder with a few torr of argon. Application of 2.45 GHz microwaves from a conventional magnetron causes plasma ignition within the argon, whose heat then liquifies and evaporates the sulfur to a final molecular density of $\sim 3 \times 10^{19}$ cm^{-3}, and $10^{-5} - 10^{-4}$ ionization fraction [7]. It is molecular sulfur transitions that are responsible for the lamp's spectral properties.

Gilles Courret et. al. [8–10] have recently observed the existence of acoustic modes inside the bulb that hold the hottest region of the plasma centrally, away from the glass. Their interest in these modes is motivated by a need to replace the mechanical rotation systems used in these lamps to distribute heat and suppress the formation of hotspots. They have suggested that continuous operation within these modes [11, 12] would obviate the need for rotation, but it is not yet clear how to maintain the stabilized mode for longer than ~ 1 s. The ability to acoustically stabilize a plasma away from its container for long periods of time would be an advance in itself and may lead to applications independent of lighting. We have organized a research effort towards this end. This basic science research is our primary motivation and so we ignore design criteria specific to lighting applications.

Although modification of a commercial sulfur plasma lamp is the fastest path to an operational, pulsed system, the ability to adjust and monitor the operation of the waveguide components are requirements that demand abandoning the minimalistic unibody construction in our academic setting. We present in this report a practical waveguide circuit, mode description, and tuning procedure appropriate for research systems. To our knowledge, such a field-level description has been absent from the literature for any type of sulfur plasma lamp. Our results regarding acoustic phenomena in the bulb will be presented elsewhere.

A necessary first step towards acoustic plasma stabilization is optimizing the magnetron's coupling to a variable plasma load. The load presented by an unlit plasma bulb is almost equivalent to that presented by the empty waveguide circuit[1]. Once ignition occurs, the plasma heats up and becomes denser, changing the load dramatically. It is difficult, if not impossible, to design a passive matching network capable of operation throughout this wide loading range. Active impedance matching networks are common in microwave-driven plasma applications [13], but are complex and expensive to implement. We instead use the same approach taken by the lighting industry: match the plasma at its hottest, densest state, and accept inefficiencies during the warm-up phase.

Figure 1a) is a photograph of the high-power waveguide circuit. It consists of a magnetron, an isolator, a directional

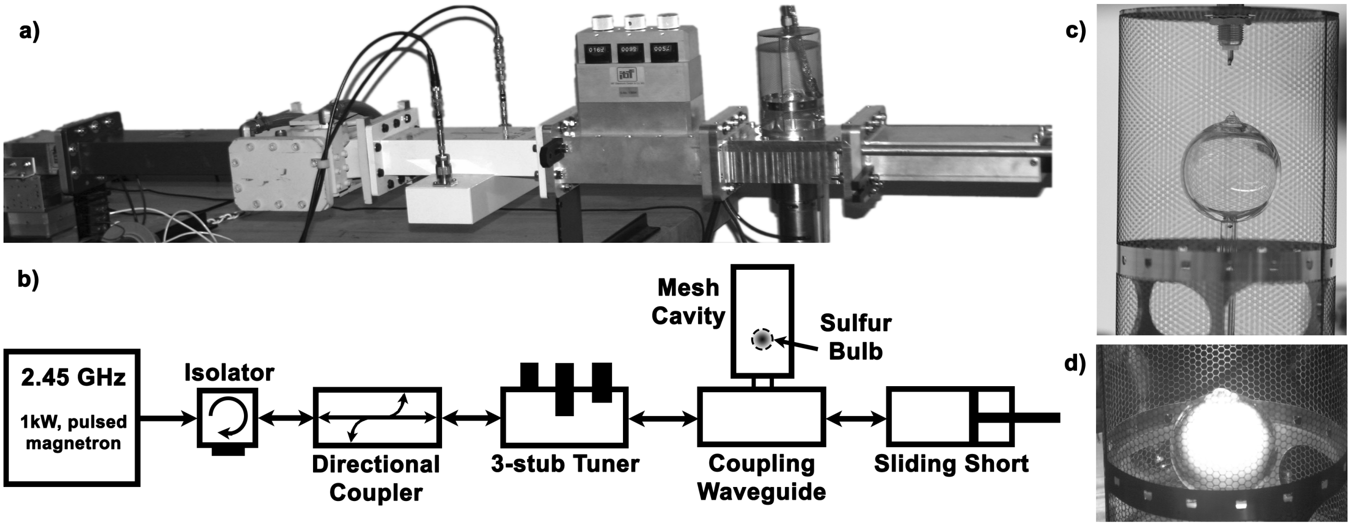

Fig. 1. Microwave system for plasma acoustic stabilization study. a) Picture and b) block diagram of the waveguide circuit constructed from WR340 components. c) The sulfur bulb sits in a metal, mesh cylinder, and is shown lit in d).

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[1] Perturbations due to the dielectric constant of the quartz bulb and sulfur powder are negligible compared to the effect of plasma ignition.

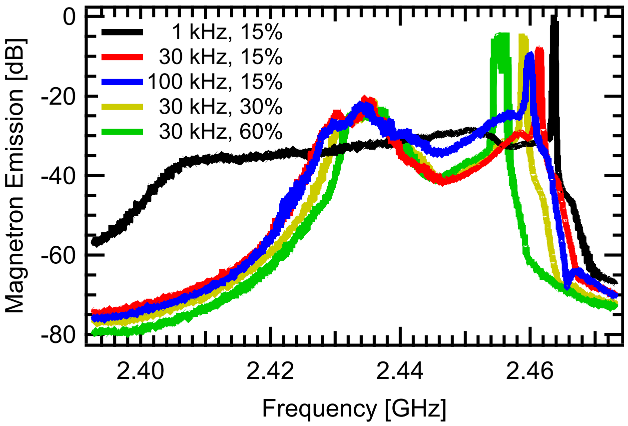

Fig. 2. The peak of the magnetron emission spectrum changes frequency by up to 10 MHz depending on the pulse frequency and duty cycle settings.

coupler, a 3-stub tuner, an aperture-coupled mesh cavity containing the sulfur bulb, and a sliding short. The magnetron high-voltage supply was purchased from the Institut d'Energie et Systemes Electriques and is described by Gilles Courret and Serge Gavin [14]. It provides pulsed power at a variable frequency of 1-100 kHz and duty cycle between 10-90% for the purpose studying the plasma acoustic response. Forward and reverse microwave power are measured through the directional coupler and optimal power transfer to the plasma is achieved with both the 3-stub tuner and sliding short as described below. A photodiode (not shown) records plasma light emission.

Plasma ignition occurs when the field within the bulb exceeds the RF breakdown threshold of low-pressure argon gas, which is a moderate $\sim 5\,\mathrm{kV\,m^{-1}}$ for our current conditions [15]. However, one could imagine future expansion of this research effort to include bulbs with different contents, with substantially higher breakdown fields. Although the high quality factor of cylindrical cavity modes (unloaded Q $\gtrsim$ 15 000 [16]) enhances the field when the source is frequency-matched to the resonant mode, the narrow line-width of such modes combined with the frequency instability of magnetrons renders them impractical to use unless they are over-coupled to a Q of a few hundred. As demonstrated in figure 2, the peak of the emission spectrum of conventional magnetrons can shift frequency by up to 10 MHz depending on the pulse frequency and duty cycle. To make matters worse, the narrow resonant modes move as well, thanks to bulb adjustments and the generally flimsy nature of the metallic mesh cavity walls that are necessary for light output.

These considerations led us to use instead what we call the hybrid mode to achieve plasma ignition. This mode has its maximum field near the coupling hole, extends towards the sliding short, and decays into the cylindrical cavity. Conveniently, its resonant frequency depends almost entirely on the position of the sliding short, which makes it easy to frequency-match to the magnetron. The cylindrical and hybrid modes are shown in figures 3a) and 3b) respectively, as simulated by the Ansys HFSS eigenmode solver. There is also the cylindrical mode with polarization perpendicular to the one in the figure 3a), but we do not excite it with our coupling hole configuration and so it is not shown here. Model dimensions were set equivalent to those in the actual system, with the depth of the three tuning stubs and position of the sliding short left variable. All waveguide components in the simulation were made of aluminum. To study the resonant modes of the cavity and short configuration, all tuning stubs

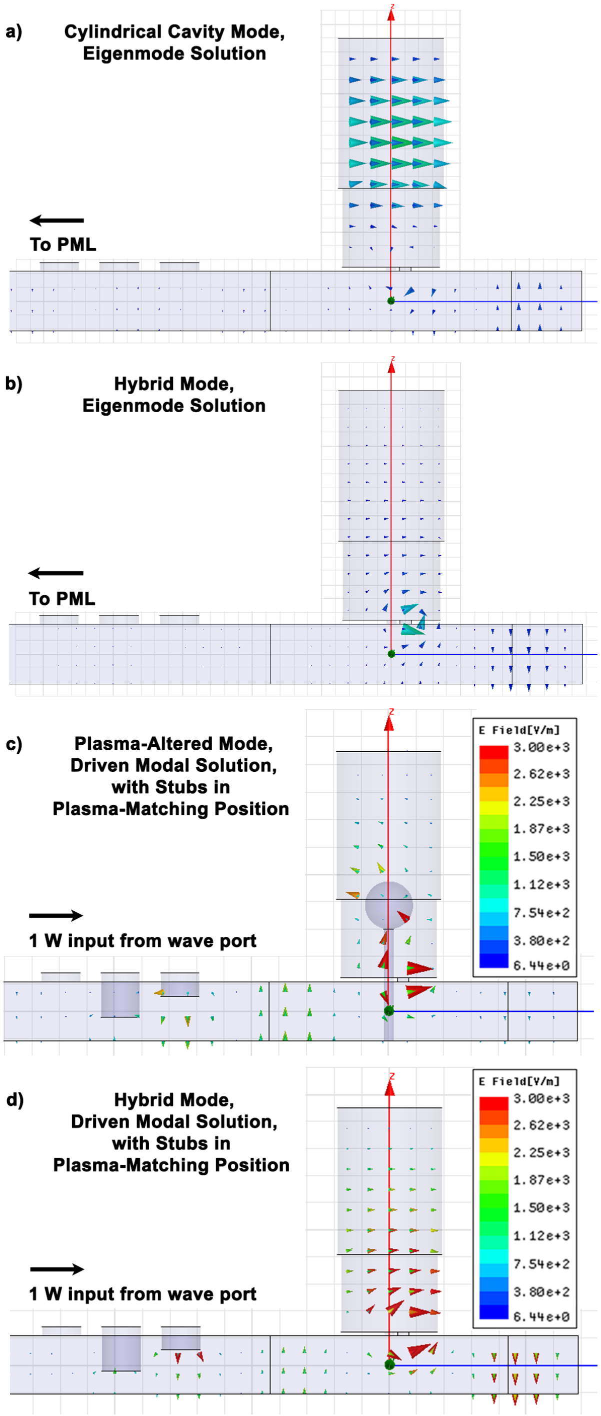

Fig. 3. Modes of the waveguide system. The cylindrical cavity mode is shown in a). Instead we work with the hybrid mode shown in b) and d). The perfectly-matched layer (PML) in a) and b) simulates the isolator in our circuit and prevents the build-up of a standing wave upstream of the cavity coupling hole. Panel c) shows the mode after plasma is fully lit. Field values given by the driven modal solutions c) and d) are for an input power of 1 W.

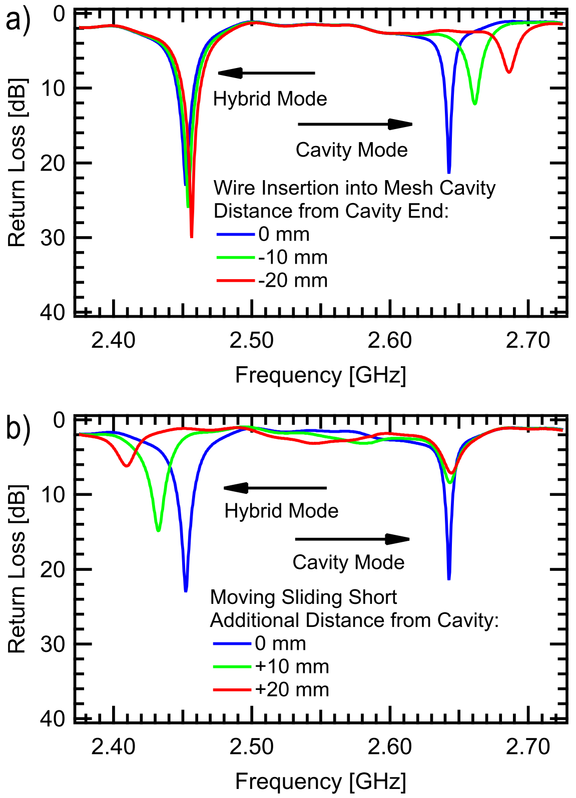

Fig. 4. Perturbations of the experimental system identify the modes expected from simulation. In a), the cavity mode shifts frequency when a metal rod is inserted into the cavity near its distal end, while the hybrid mode remains unchanged. In b), the hybrid mode shifts frequency in response to moving the sliding short, while the higher frequency mode remains fixed in frequency.

were completely retracted. A perfectly matched layer (PML) was added at the input of the waveguide to simulate the isolator.

We experimentally verified the existence and general properties of the cavity and hybrid modes by substituting an HP 8720C network analyzer and SMA-to-waveguide transition for the magnetron and isolator. Introducing a small amount of loss by lining part of the cavity wall with carbon sheet lowers the unloaded Q and greatly facilitates viewing the resonant lines, which would otherwise be too over-coupled to be visible. The two modes are visible in the return loss plots of figure 4. We find that the higher-frequency mode shifts frequency in response to insertion of a thin metallic rod into the distal end of the cylindrical cavity, but not when the sliding short is moved, thereby identifying it as the cylindrical cavity mode. On the other hand, the lower-frequency mode shifts frequency when the sliding short is moved, but not when the rod is inserted into the cavity. We therefore identify the lower-frequency mode as the hybrid mode. The frequency shifts quantitatively match those expected from simulations. Changes in the cylindrical mode return loss as the sliding short is moved, and changes in the hybrid mode return loss as the rod is inserted into the cavity, reflect changes in their coupling and are ignored for this purpose.

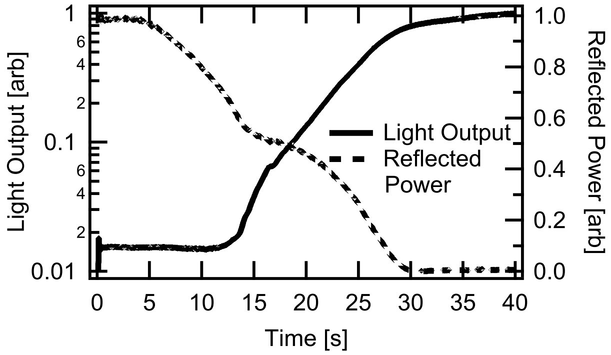

Fig. 5. Sulfur evaporation increases light emission and improves microwave impedance matching. The tuning stubs are set so that optimal matching occurs when the bulb is fully lit, as indicated by the reflected power going to zero. Typical time-averaged power levels are 800-1100 W.

Next we configure the 3-stub tuner so that all microwave power is absorbed by the plasma once it is fully lit. This is distinguished from setting the tuner for maximum field strength at the unlit bulb. While in principle impedance matching could be done experimentally with live feedback, the speed of plasma heating makes it difficult to track by hand. Our approach was to use simulations to acquire a rough estimate of the correct stub position, and then fine-tune *in-situ*. We defined a custom “sulfur plasma” material in HFSS with real permittivity and permeability equal to 1, and bulk conductivity equal to what we expect in the plasma. The material is not a plasma; it is a solid material with conductivity similar to the plasma, used for estimation purposes. Based on [7] we expect a conductivity of $1 - 100\ \Omega^{-1}\mathrm{m}^{-1}$ depending on temperature and sulfur density, and use $60\ \Omega^{-1}\mathrm{m}^{-1}$ in our simulations. For comparison, this conductivity range is between that of seawater and amorphous carbon. We place a sphere of “sulfur plasma” in the cylindrical cavity at the bulb position, and use a driven modal HFSS solution type to calculate scattering parameters. Stub positions are manually adjusted in HFSS until the plasma bulb is impedance matched. Optimal depths found are 11 mm, 26 mm, and 0 mm, ± 1 mm, for the closest, middle, and furthest stub from the cavity.

Including the plasma in the simulation qualitatively changes the hybrid mode to that in figure 3c). In going from empty space to an estimated conductivity, we have taken into account sufficient loading to reliably determine approximate stub positions. Nevertheless, the actual plasma conductivity varies in space and time and with microwave power, so caution is warranted in interpreting the particular field values in the figure.

We confirmed that field values are reasonable to achieve plasma ignition with this stub configuration by generating a driven-modal solution for the empty waveguide system. Figure 3d) shows the driven hybrid mode with the plasma-matching stub positions, but before plasma ignition. Field values in the plot are for 1 W incident power. With 1 kW, we can expect field values about $30\times$ higher, and a peak field of about $90\ \mathrm{kV\ m}^{-1}$. Although the bulb is not located at the field maximum, it is close enough to reliably ionize the argon. The Q of the hybrid mode in this configuration is ~ 1000, so it needs to be frequency matched to the magnetron within a couple of megahertz for these values to be achieved.

Tuning of the actual system proceeds as follows: First the magnetron frequency is measured. The nominal 2.45 GHz frequency defined by the ISM band is not accurate enough for matching to resonant modes of even moderate Q. The magnetron and isolator are then replaced with a network analyzer to view the resonant modes of the system with all tuning stubs retracted. The position of the sliding short is adjusted so that the frequency of the hybrid mode matches that of the magnetron, ignoring changes in coupling. According to figure 4, the resonant frequency changes by about 2 MHz per millimeter of motion, and therefore matching to the hybrid mode requires a positioning accuracy of 1 mm. Once matched, the sliding short is locked in place and does not change for the remainder of the experiment. The magnetron and isolator are re-installed and the stubs are set to the plasma-matching positions given coarsely by HFSS. Since the field achieved within the bulb in this configuration is sufficient to cause ignition, the stubs do not need to be changed during and between runs. After ignition, the sulfur begins to melt and evaporate, and light emission increases from the relatively dim argon emission to the much brighter molecular sulfur emission. Simultaneously, the microwave pulses are absorbed at an increasing rate as the matching improves.

If the stubs are set properly, microwave reflection will settle to zero once the bulb is fully heated. This process is understood as an initially over-coupled system increasing its load until it becomes critically coupled. However, the tuning stubs are unlikely to be at the optimal position on the first iteration, and the reflection will follow one of two different courses depending on whether increased or decreased coupling is needed. If the reflection drops initially, but never reaches zero, the coupling does not reach critical and needs to be decreased. If the reflection drops, reaches zero, and then begins to rise, then the system has gone from over-coupled to under-coupled and the coupling needs to be increased. This process may require iteration until optimal stub positions are found. We find that these positions are weakly dependent on the time-averaged microwave power, but not on the pulse frequency or duty cycle at a given power.

Figure 5 displays both light emission and microwave reflection traces during the bulb warm-up period. The light output follows an “S” curve, during which the reflected power drops from 100% to < 1%. Despite all the sulfur evaporating after about 30 s, the light output continues to rise slowly for 15-30 min (not shown), which we attribute to the experimentally observed settling of the magnetron output power as the system warms up. The increased heating over this warm-up time has negligible effect on the reflected power, implying that relatively small changes in conductivity after all the sulfur has vaporized negligibly change the matching compared to the evaporation of the sulfur, and validates our order-of-magnitude estimate for the final plasma conductivity in the simulation.

We have constructed a pulsed, high-power 2.45 GHz system specifically tailored for studying acoustics in dense, weakly ionized gas. Use of the hybrid mode allows us to reliably ignite, sustain, and impedance match a sulfur plasma with a passive waveguide circuit. We suspect this mode of operation has been used by others, but a prescription for its construction and a detailed, field-level description of its tuning was previously unavailable. This well-understood system allows us to study acoustics in plasmas in a controlled environment.

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Putterman is a Fellow of the Acoustical Society of America and the American Physical Society and a past recipient of an Alfred P. Sloan Fellowship. He was named the UCLA 2010−2011 Faculty Research Lecturer. Nature profiled his out-of-the-mainstream approach to science in their October 2005 issue.