A Directional Microplasma Thruster Exhibiting a Switchable Intense Plasma Coupling

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ABSTRACT Conventional cold and warm gas thrusters with low specific impulses and thrust greatly limit the capability of nanosatellites to conduct meaningful plane and attitude changes in space. This work shows that a novel flexible microplasma thruster (FPT) technology can yield high thrust performance at sufficient specific impulse. The FPT consisting of a seven-jet bundle generated a maximum thrust of 61.9 mN with helium at less than 30 W in ambient atmosphere, and 64.3 mN in vacuum at less than 2 W via jet-to-jet coupling. To further enhance the thrust contributions from both the plasma emission and gas discharge, a novel micro-nozzle was embedded at the end of the glass fiber. The resulting supersonic gas-exhaust velocity from the nozzle increased the thrust output of a single fiber by 300%. This versatile system is a promising microplasma thruster technology suitable for flight demonstration onboard a CubeSat platform, thus changing the nano-satellite paradigm from passive sensor carriers to a fully capable spacecraft.

INDEX TERMS Microplasma, thruster, plasma coupling, microplasma nozzle effect.

I. INTRODUCTION
Nanosatellite platforms are rapidly gaining popularity as alternatives to traditional satellite systems, due to their decreased production and delivery costs [1]–[7]. Nanosatellite use is projected to increase by over 10 times during the next five years [6], and will secure a dominant role in satellite applications. However, these satellites are less than 10 kg, and typically occupy less than 3,000 cm³, which presents limitations to the capabilities of on-board thrusters. Plasma-based thrusters have been extensively researched for this specific role in nanosatellites over conventional thrusters as they have reduced propellant consumption and exhibit higher specific impulse [8]–[22]. They are small enough for use on many cubesats and other similar nanosatellite platforms with typical dimensions less than 20 cm × 20 cm × 30 cm, simply designed and require neither explicit neutralizers nor biased electrodes [10]–[22]. However, these systems exhibit relatively low thrust output (<0.3 mN), and even Hall thrusters of this size generate less than 7 mN thrust (7). These thrusters are also composed of rigid materials, which restrict their flexibility for precise positioning and station-keeping, as well as places limitations on the configuration of platform for thruster installation. To address these issues, a breakthrough in both plasma science and thruster design is needed.

We investigate a recent phenomenon that occurs in arrays of collected plasma jets where the nearby plumes converge into a highly energetic central plume via a jet-to-jet coupling effect [23]–[25]. This convergence of the cold plasma jets presents several advantages [26]–[30], as it exhibits increased energy efficiency as well as a notable increase in thermal energy. This phenomenon is demonstrated in the application of a flexible microplasma thruster (FPT) system based on an array of hollow-core glass fibers with micrometer-scale inner diameters that utilizes jet-to-jet coupling effects to increase thrust performance, confirmed experimentally in both atmospheric and vacuum conditions. This proposed FPT is inherently flexible and chemically robust, and can be fabricated in extended lengths. Each glass fiber bundle in the FPT system is self-addressable, and the system can be vectored. We also discuss the mechanism behind the jet-to-jet coupling effect from a fluid dynamics [31]–[34] and plasma physics perspective. The FPT is further enhanced by incorporating a micro-nozzle structure at the end of the device, to increase thrust, and produce a remarkable effect of sustaining plasma emissions at the throat of the micro-nozzle throughout an entire alternating
electric field cycle. This micro-nozzle phenomenon, which has yet to be reported in plasma science, is shown to produce an efficient plasma emission with increased energy density.

II. RESULTS AND DISCUSSION
A. JET-TO-JET COUPLING EFFECT
In previous research, we used a multi-tube honeycomb-structured quartz tube array-based helium (He) plasma device to create intense plasma emissions via jet-to-jet coupling [23]–[25]. In ambient air, we observed two plasma modes within the same plasma array structure under various gas flow and applied voltage conditions: an intense plasma mode and the well-collimated plasma mode [23]. The intense plasma mode shown in Fig. 1 (a) demonstrates the characteristics of the jet-to-jet coupling effect, during which an array of seven quartz tubes create a stable intense center plasma stream with each outer jet clearly interacting with the center plume. A 4-mm wide strip of carbon tape was wrapped around the center tube only, 8 mm from the end of the jet. No copper tape was applied to the six outer tubes individually; the tubes were instead arranged into the desired honeycomb structure, with copper tape wrapped around the outside of the gathered tubes, which resulted in a more compact design with each tube physically contacting the adjacent outer tubes, as well as creating a floating electrode center tube. More details on the microplasma jet device and experimental setup are included in Methods. The intense plasma generated by the jet-to-jet coupling effect observed in the multi-tube array-based plasma device has been shown to significantly increase the strength of the plasma and the optical intensity by four times [23].

The temperature of neutral species was measured using optical emission spectroscopy (OES). For measuring gas temperature from the OES, the emission spectrums of the rotational ($T_{rot}$) and vibrational ($T_{vib}$) structures of molecular species should be understood; Fig. 1 (b) shows the measured $T_{rot}$ obtained from OES (see Methods). As the gas flow rate was decreased from 3 slm (with 8.0 kV applied voltage and He gas) in the laminar flow regime, the plasma discharge mode transitioned from the well-collimated mode to the intense mode at 1 slm (with 9.5 kV and He gas). In the well-collimated mode, the measured gas temperature $T_{rot}$ at the He gas discharge is approximately 321 K. However, $T_{rot}$ was 391 K during the intense plasma mode, an increase due to the enhanced plasma density resulting from the coupling effect between the inner and outer plasma jets. The increased plasma density resulted in the greater number of collisions of the charged species (electrons and ions) with neutrals, thus increasing the $T_{rot}$. Therefore, the activation of the intense plasma mode can increase the plasma density.

Infrared (IR) emission measurements were taken to evaluate the plasma quality improvement from the intense plasma mode, relative to the well-collimated mode of the jet, shown in Fig. 1 (c). Although there is a distinct relationship between increasing the gas flow rate and a resulting increase in plasma intensity while operating in either mode, the jet-to-jet coupling effect produced a highly-energetic plasma while operating at less than half of the gas flow rate of the well-collimated mode. The driving voltage used to generate the intense plasma mode (8.9 kV) was 14% greater than the voltage used for the well-collimated mode (7.8 kV), yet the plasma intensity resulting from the intense plasma mode was approximately four times larger in the coupled array (Fig. 1 (c)). This nonlinear response was a result of the coupling phenomenon, not the slight increase in input electric power.

FIGURE 1. Characteristics of jet-to-jet coupling effect. (a) Angled view image of plasma jet array device. The intense plasma is directed towards a glass plate to demonstrate emission intensity. Inset: side view image of plasma jet. (b) Measured rotational temperature ($T_{rot}$) from plasma jet array device. $T_{rot}$ was acquired from both well-collimated and intense plasma modes. Left inset: side view image of well-collimated mode, right inset: side view image of intense plasma mode. (c) Integrated value of IR emissions. Data for each operating mode is displayed for a fixed observation distance of 15 mm. Mode transition under these conditions occurs between 1.42 and 1.89 slm.
FIGURE 2. Experimental investigation of jet-to-jet coupling effect mechanism. (a) ICCD image of well-collimated mode with horizontal profiles of the light emission intensity (shown in the left inset). (b) The applied voltage with tic marks indicating frame capture points. (c) ICCD image of intense plasma mode with horizontal profiles of the light emission intensity (shown in the right inset). Color bars: light intensity rubric. (d) Time-resolved discharge images taken by a high-speed ICCD camera with fixed exposure time of 1 µs. The top and bottom of each image shows the well-collimated and intense modes, respectively. The images correspond to the respective points along the applied voltage waveform in B, designated as A–H. (e) Schematic model of jet-to-jet coupling mechanism. Note that the events are interdependent and occur simultaneously in a self-sustaining system.

Time-resolved discharge images of plasmas from well-collimated and intense modes have been investigated through the use of a high-speed intensified charge-coupled device (ICCD, Princeton Instruments PI-MAX4) [35]. Fig. 2 shows the discharge images for four consecutive time frames in positive and negative cycles with a fixed exposure time of 1 µs (see supplementary video 1 for intense mode for frames with fixed exposure time of 0.5 µs). In the positive cycle when the electrode is an anode, the discharge for the well-collimated mode begins near the grounded glass plate, the location of the cathodic emissions from electron impact ionizations. The discharge for this intense mode indicated strong emissions near the powered electrode. The greater speed of the discharge ignition than that of the well-collimated mode made it difficult to observe the cathodic emissions for the intense mode. In the negative cycle when the electrode is a cathode, the emission intensity of the well-collimated mode remained equally distributed across the tubes, but was notably weaker than the emission from the positive cycle. In contrast, the plasma plume from the intense mode during the negative cycle became much stronger than in the positive cycle. Based on the time resolved images for the intense mode, although the center plasma plume diverges for the positive cycle, it is tightly focused for the negative cycle when the electrode and glass plate are a cathode and anode, respectively, which suggests the presence of a self-sustaining electromagnetic (EM) field that drives the confinement of the outer plumes.

The seemingly continuous medium of a plasma stream generated by typical plasma jets actually consists of individual pulses of plasma bullets that correspond to the frequency of the applied voltage, and propagate down the device at velocities much higher than the surrounding gas flow [36], [37]. From the ICCD images with a 0.5 µs fixed exposure time, the average bullet velocity during the
The jet-to-jet coupling mechanism is described by the schematic model in Fig. 2 (e), based on ICCD imaging, gas temperature, optical emission, and fluid dynamics. Once the device is fully operating in the well-collimated mode and plasma discharge is present, jet-to-jet coupling can be induced by reducing the gas flow rate or raising the applied voltage sufficiently to initiate a transition into the intense plasma mode. Under transition conditions, the plasma is focused along the edge of the jets at the end of the device, as shown in Fig. 2 (e), with the highest intensity occurring in the center tube. When the flow rate is reduced beyond the critical point, a velocity offset between the inner and outer plumes of approximately 5 km/s is observed, denoting an acceleration of charged particles in the center plume. The plasma focused at the edge regions show a growing mutual electromagnetic attraction to the center jet, due to the central overlap of the surrounding plumes at the outlet of the device. Eventually, the EM interactions between the jets overcome the separation caused by emission velocities, and the outer plumes are pulled inward to the center jet, transitioning to a collected intense plume via jet-to-jet coupling, shown in Fig. 2 (e). This intense plume is contained within a bounded volume region with diameter ~1.25 cm established by the electromagnetic field from the plasma interactions along the plume. From Bernoulli’s equation [31]–[33], the effective constriction of the plasma flow after emission from the device results in a corresponding increase in fluid velocity and kinetic energy (see Methods), both of which were observed through ICCD imaging and rotational temperature calculation, and results in a highly intense and energy dense plasma emission. The jet-to-jet coupling effect links the plasma flow inside of the center jet and at the edge of the outer tubes, with the extended converged plume outside the device to form a self-sustaining coupled plasma system.

The intense plasma mode represents a controllable transition from cold to quasi-thermal plasma. A further increase in the applied voltage will result in an extended mode transition to a highly-reactive thermal plasma mode capable of generating higher temperatures. When the device switched to the intense plasma mode, rapid etching and melting of a glass substrate was achieved, as shown in Fig. 3 (a). During this mode, a highly energetic and concentrated plasma bores into the protective glass layer, as shown in the ICCD images in Fig. 3 (b). While the plasma generated by the device employed in this study is considered non-thermal, as it does not exist in a thermal equilibrium, the topology of the impact sites of various substrates indicates the plasma was able to penetrate through a 1.5 mm thick sheet of polytetrafluoroethylene (PTFE), and showed signs of etching, melting, and chemical interactions in both glass and PTFE, which suggests the presence of a thermal mechanism occurring during the thermal plasma mode.

**B. FLEXIBLE MICROPLASMA THRUSTER**

In order to highlight the significance of the jet-to-jet coupling effect discussed in this study, we fabricated a series of flexible microplasma devices for potential use as thrusters for small spacecraft, such as the cubesat nanosatellite package. The devices were constructed using glass fibers, which provided a high degree of flexibility, and allowed for down-scaling of the jet-to-jet coupling effect to micrometer dimensions.
Device analysis was conducted via optical emissions, visual observation of coupling effects, and thrust measurements in both atmospheric and vacuum conditions using a calibrated pendulum thrust stand.

Fig. 4 shows the various microplasma thrusters: a single glass fiber (Fig. 4 (a) and supplementary video 2), an array of seven single fibers (Fig. 4 (b) and supplementary video 3), and a single bundle with seven fibers (Fig. 4 (c) and supplementary video 4). A simple microplasma thruster bundle was developed for our jet-to-jet coupling effect, a schematic of which is shown in Fig. 4 (d). The structure and design matches the conventional jet device with a reduced size, using fibers instead of glass tubes. Each optical fiber within this array has an inner diameter of 353 µm and an outer diameter of 477 µm (see Methods), with the center-to-center distance between the two adjacent optical fibers at about 600 µm. The single bundle of seven fibers shows a significant increase in the plasma’s optical intensity compared to a single fiber operating at the same voltage (sinusoidal voltage waveform with a peak voltage of 14 kV and frequency of 33 kHz). Additionally, Figs. 4 (b) and (c) show that the plume length of the bundle is increased to over 4.2 cm, compared to the array of seven single fibers with a plume length of approximately 1.2 cm while using the same gas flow rate and velocity.

Specifically, the emissions from each jet are gathered in the jet-to-jet coupling effect occurrence area, shown in Fig. 4 (c),
where jet-to-jet coupling is responsible for generating the plasma’s extended area in the plume. This extended area can contribute to enhanced plasma thrust functions. These devices operate without the presence of an electrode beyond the plasma exhaust, and there is no change in the measured current during jet-to-jet coupling. As such, the jet-to-jet coupling behavior in the FPT is a new phenomenon, and is not indicative of common streamer discharge. The incorporation of the seven-fiber bundle does not sacrifice the inherent flexible and robust properties of the glass fiber, as shown in Fig. 3e; both the intensity of jet-to-jet coupling and the versatility of the glass fiber are preserved. These seven-fiber bundles were implemented in a novel FPT system consisting of three vertical arrays of five bundles each, shown in Fig. 4 (f) and supplementary video 5. This low profile microplasma thruster is highly flexible and lightweight, providing a system that allows thrust vectoring with a negligible impact to payload.

Fig. 5 demonstrates the maximum thrust (see Methods) under the various structures and discharge conditions, such as a single fiber, seven single fibers with glow discharge, and a single bundle with seven glass fibers with both glow and arc discharges. As shown in Fig. 5 (a), the single bundle of seven fibers produced a plasma-only thrust 70% greater than the array of seven single fibers at the same gas flow rate and velocity, as a result of jet-to-jet coupling in the bundle array. The increase in the thrust was achieved with an input electrical power of less than 30 W, whereas comparable electric propulsion systems require above 1 kW [8]–[10]. The single bundle with seven fibers under glow discharge generated maximum plasma-only thrusts of 7.8 mN with He and 11.2 mN with Ar, and the combined gas-plasma totals were 61.9 mN and 70.9 mN with He and Ar respectively. Furthermore, changing the plasma ignition in the bundle from glow to arc discharge doubled the realized plasma thrust, due to an increased plasma density in which the plasma-only contributions were about 15.7 mN with He and 23.2 mN with Ar, and the combined gas-plasma totals were 69.8 mN and 82.9 mN for He and Ar, respectively, as shown in Table 1.

In the single bundle with seven optical fibers, the measured gas temperature $T_{rot}$ is about 350 K at glow plasma discharge. On the other hand, a remarkable increase in the $T_{rot}$ to 430 K was observed from the arc plasma discharge. This increased plasma density resulted in a substantial increase in the number of collisions between charged species (electrons and ions) and neutrals, thus resulting in an increase in $T_{rot}$. Therefore, plasma densities can be quite high from arc discharges, as compared to glow discharges.

In order to further investigate the FPT system, thrust measurements were obtained in both vacuum and ambient conditions using a calibrated pendulum thrust stand. Due to the flexible nature of the device, modifications to the thrust stand were needed to ensure stable operation for thrust measurements as shown in Fig. 6 inset. The ambient atmosphere measurements using the pendulum stand confirmed that the
In an effort to further explore the versatility of the flexible microplasma thruster, a glass fiber with a micrometer scale converging-diverging (CD) nozzle structure was fabricated (see Methods) to improve thrust function. This device is the first of its kind, and is capable of sustaining an appreciable plasma discharge even when the electric field is absent; this unique effect has never been reported in plasma physics before (supplementary video 6 for standard fiber, and video 7 for fiber with micro-nozzle). The typical discharge profile of plasma generated from a sinusoidal voltage waveform consists of plasma ignition only occurring when the positive and negative electric fields are generated, as shown in supplementary video 6. However, the fiber with micro-nozzle exhibited a plasma discharge that remained ignited throughout the entire voltage cycle, resulting in a highly efficient plasma emission with high energy density, as shown in supplementary video 6 and Fig. 7. The converging-diverging nozzle design in Fig. 7 (a) can be used to invoke supersonic gas flow velocities by creating a choked flow condition described by the Venturi effect [32]–[34] (see Methods). Operating at 0.38 standard liters per minute (slm), the gas velocity in the micro-nozzle is accelerated from 64.29 m/s at the inlet, to 355.54 m/s at the throat of the nozzle, satisfying a beneficial choked flow condition. The gas exhaust velocity after the throat increases as the nozzle expands, and is expected to reach approximately 839 m/s under optimal conditions, creating supersonic flow that is highly desirable for thrust applications.

Furthermore, from the ICCD images in Fig. 7 (c), taken in 1 µs frames, the plasma bullet velocity in the nozzle thruster is 8 – 10 km/s, while the plasma velocity in a single standard glass fiber is typically 5 – 7 km/s; the nozzle structure is creating a condition that is favorable for an intense plasma emission. The specific impulse of the single standard fiber is approximately 510 – 720 s, while the nozzle thruster exhibited an increased specific impulse at 820 – 1020 s (see Methods). The frames D and H in Fig. 6c show the distinct microplasma-nozzle effect where the ignited plasma remains active even when the alternating electric field is not present. Additionally, Fig. 7 (d) shows that a remarkable gain of 50% in the plasma thrust and 200% in the combined thrust is achieved as a result of this effect. It is expected that as the nozzle accelerates the gas to supersonic velocity, the subsequent rise in neutral particle kinetic energy forms a highly active region immediately following the choke point in the nozzle. This energetic region is capable of sustaining priming particles for plasma ignition during the periods between the main discharge peaks, which allows for an atypical discharge behavior that continues throughout the voltage cycle. The use of the nozzle not only increases both the gas and plasma bullet velocities and the device’s thrust capacity, but also prolongs the effective lifespan of the active plasma plume, translating to enhanced plasma efficiency and emission strength.

### TABLE 2. Vacuum performance parameters.

| Gas       | Mass flow rate [mg/s] | Number of tubes | Voltage [kV] | Power [W] | Thrust [mN] | Specific impulse [s] |
|-----------|-----------------------|-----------------|--------------|-----------|-------------|---------------------|
| He        | 0.6                   | 7               | 1.6          | 50        | 64.3        | 10700               |

### FIGURE 6. FPT performance of jet-to-jet coupling in vacuum conditions. Single bundle with 7 glass fibers with intense plasma discharge via jet-to-jet coupling effect in vacuum. Inset: Calibrated pendulum thrust stand and modified FPT mount. FPT device was inserted into a fused-silica tube and fixed in place using low vapor pressure epoxy, mounted between two PTFE sheets.

The practical significance of the jet-to-jet coupling effect was highlighted under vacuum conditions, where the plasma exhaust exhibits a linear horizontal plume during operation, as shown in Fig. 6. The plume visibly extended 16.7 cm from the device while maintaining a confinement diameter of 4.5 cm, without the presence of an external magnetic field. Although the appearance of the coupling phenomenon shows some differences between vacuum and ambient conditions, there is an identifiable coupling effect occurrence area extending 1 cm from the exit of the FPT device where the plumes from the seven fibers converge before expanding into the plasma extended area in the exhaust. We assume that the confinement behavior identified in the plasma extended area is a result of a self-sustaining electromagnetic field that is generated through jet-to-jet coupling within the effect occurrence area. As a result, the newly proposed microplasma thruster using flexible glass fibers can generate the intense plasma mode with a strong plasma emission and a high thrust function in both vacuum and ambient atmosphere conditions. The jet-to-jet coupling effect is verified and observed in vacuum conditions, and contributes to a higher maximum thrust in the FPT without increasing the input power requirements.
FIGURE 7. Single glass fiber microplasma thruster using micro-nozzle. (a) Side view of the novel micro-nozzle structure. (b) The applied voltage with tic marks indicating frame capture points. (c) Time-resolved discharge images taken by a high-speed ICCD camera with fixed exposure time of 1 µs. The images correspond to the respective points along the applied voltage waveform in B, designated as A – H. Insets on each figure show the alignment of the nozzle structure during the plasma emission. (d) Thrust improvement achieved with single fiber nozzle thruster. Thrust results are shown for the single fiber thruster, with and without the microplasma-nozzle, considering both the thrust contributions from the plasma emission, and the total thrust from the plasma and gas exhaust. Scale bar, 200 µm.
The acceleration mechanism is electromagnetic plasma bullets and pressure based (expanded gas from the nozzle).

III. METHOD
A. PLASMA JET AND MEASUREMENT SYSTEM
In this paper, we detail the creation of a plasma-based thruster consisting of seven round glass tubes arranged in a honeycomb order. Each jet tube was 15 cm in length, with an inner diameter (ID) of 1 mm and an outer diameter (OD) of 2 mm, with the center-to-center distance between the two adjacent quartz tubes at 2.5 mm. A 4 mm wide strip of carbon tape was wrapped around the center tube only, 8 mm from the end of the jet. No copper tape was applied to the six outer jets individually; the tubes were instead arranged into the desired honeycomb structure, with copper tape wrapped around the outside of the gathered jets, which resulted in a more compact design with each tube physically contacting the adjacent outer tubes, as well as creating a floating electrode center tube. A 0.8 mm-thick glass plate with a transparent indium tin-oxide (ITO) film coating on one side was placed with the uncoated glass side facing the jet, that acted as a dielectric barrier. The ITO plate was implemented to allow jet-to-jet coupling to be triggered over a greater range of gas flow rates and applied voltages, for more thorough measurements. A high-voltage probe (Tektronix P6015A) was connected between the power supply and the oscilloscope (Tektronix TDS3014C) to measure the input driving voltage. In the driving circuit, an inverter was used to amplify a low primary voltage to a high secondary voltage. The driving circuit generated a sinusoidal voltage of several tens of kilovolts with a frequency of several tens of kilohertz. High-purity helium or argon gas (99.999%) was used as the discharge gas, and the photo-sensor amplifier (Hamamatsu C6386-01) was used to investigate the plasma infrared (IR) emission. The wavelength-unresolved optical emission waveform from the photo sensor amplifier was plotted on the oscilloscope. In order to avoid the external light signals a glass sheet 2-mm thickness was placed in front of the photo-sensor amplifier. The resulting distance between the end of the device and the measurement lead was about 10 mm. In order to investigate the plasma gas temperature, the emission spectra of the microplasma jets were monitored with the fiber optic spectrometer (Ocean Optics, USB-4000UV-VIS). The distance between the end of the device and the spectrometer was about 10 mm. All photographs of the devices and plasma plumes were taken with a DSLR camera (Canon EOS Rebel T1i) with a Macro 1:1 lens (Tamron SP AF 90mm F2.8 Di). The time-resolved discharge images of the jets were taken with a high-speed intensified charge-coupled device (ICCD, Princeton Instruments Pl-MAX4). The direct thrust measurements of each thruster were then performed using a micro balance under end of the plasma plume, and then verified using a pendulum thrust stand with calibrated weights in both ambient atmosphere and vacuum conditions.

B. ROTATIONAL TEMPERATURE
The spectrum of the N₂ second positive system (C³Π_u(v′, J′) \rightarrow B³Π_g(v′′, J′′)) is used [38], [39]. In the energy level transition of C³Π_u(v′, J′) \rightarrow B³Π_g(v′′, J′′), the emission intensity of the spectrum is expressed as:

\[ I_{B,v′,J′,v′′,J′′} \propto K \times q_{v′,v′′}S J_{v′,v′′} \left( \tilde{v}_{J′,J′′} \right)^4 \]

\[ \times \exp \left[ -\frac{hc}{k_B} \left( \frac{G(v)}{T_{vib}} + \frac{F(v', J')}{T_{rot}} \right) \right] \]

where \( T_{vib} \) and \( T_{rot} \) represent the Boltzmann equilibrated vibrational and rotational temperature, respectively. \( K \) is a constant for considering geometrical, spectrometer sensitivity, and electronic transition factors, \( q_{v′,v′′} \) is the Frank-Codon factor [40], \( S_{J′,J′′} \) is the Hoenl-London factor [41], [42], \( \tilde{v}_{J′,J′′} \) is the emission light frequency, \( h \) is the Plank constant, \( c \) is the speed of light, and \( k_B \) is the Boltzmann constant. The subscripts \( J′, J′′ \) and \( v′, v′′ \) are the upper and lower states of the rotational and vibrational transitions, and \( G(v') \) and \( F(v', J') \) are the vibrational energy and rotational energy.

In the actual OES measurement, the finite spectral resolution of the optical spectroscopy results in a broadening of the line spectrum. This broadening effect, where the shape is generally a Gaussian function, should be considered in the theoretic spectrum, which can then be calculated from the convolution of Eq. (1) and the Gaussian function:

\[ I(\lambda) = \sum_{v′,v′′,J′,J′′} I_{B,v′,J′,v′′,J′′} \times \exp \left[ -\frac{1}{2} \left( \frac{\lambda - \lambda_{B,v′,J′,v′′,J′′}}{\Delta \lambda} \right)^2 \right] \]
gas velocity is less than approximately Mach 0.3, the fluid can be approximated as an incompressible flow. As the outer plumes are pulled inward by the center jet in the array device, the effluent gas is constricted down from the larger effective sectional area of the intense plasma plume. According to Bernoulli’s equation, the total energy density before and after a constriction must be identical as expressed as \( \frac{p_1}{\rho g} + \frac{u_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{u_2^2}{2g} + z_2 \), where \( p \) is pressure, \( \rho \) is density, \( g \) is the acceleration due to gravity, \( u \) is the velocity, and \( z \) is the elevation. The kinetic energy \( \frac{u^2}{2g} \) increases with the velocity, as the pressure energy \( \frac{p}{\rho g} \) is reduced at the constriction.

**D. THRUST MEASUREMENT**

The exhaust discharge from each thruster was directed towards the surface of an Acculab digital microbalance at a fixed distance of 7 cm from the end of the plasma plume. All surfaces were electrically ground to prevent the accumulation of charge to mitigate residual electrostatic forces. The balance was placed into a specialized chamber in order to prevent interference from ambient conditions. From the mass measurement, thrust was calculated from Newton’s second law, \( F = ma \), where \( a \) is the acceleration due to the gravity of Earth, and \( m \) is the mass. The thrust was first calculated for a pure gas discharge without the presence of plasma. A second measurement was conducted with the full discharge including the plasma ignition, with the difference between the gas thrust and full system thrust measurements then used to determine the resulting individual thrust contribution from the plasma. Additionally, the thrust of the FPT system was verified under both ambient and vacuum conditions using the standard technique of a pendulum thrust stand with calibrated weights.

**E. HOLLOW CAPILLARY GLASS FIBERS FABRICATION**

The authors fabricated hollow glass fibers at Clemson University using a custom-designed commercial-scale Heathway optical fiber draw tower. Briefly, a fused silica tube (General Electric (GE) 214) with an inner diameter of 19 mm and outer diameter of 25 mm was drawn at a temperature of approximately 1900 °C and rate of approximately 6 m/min. At this temperature the silica glass can be drawn into fiber while maintaining the hollow core.

**F. MICRO-NOZZLE DEVICE PREPARATION**

The fiber was taken to AFL Telecommunications for further processing. The outer polymer jacket of the fiber was removed for 3 cm from the end, and the fiber was placed in an AFL LZM-100 CO₂ glass processing system for precision modification. A CO₂ laser was used to soften the glass, while the fiber underwent a continuous and constant taper rate in order to impinge the desired nozzle structure. The fiber on both sides of the target site underwent bilateral manipulation throughout a 60 second rotation, along with modulation of the laser power level, until nozzle dimensions were satisfied. This automated processing technique allows for precision control of the specific dimensions of the nozzle, including flare angle and throat diameter. It is important to note that the nozzle is not a separate attachment; rather it is an emergent structure from the same continuous strand of glass fiber, which results in an inherently robust design.

**G. NOZZLE EXHAUST VELOCITY**

When the gas velocity exceeds Mach 0.3, it is defined as compressible, at which point the velocity change per cross-sectional area change is described by the equation \( (1 - M^2) \times \frac{du}{A} = -\frac{dA}{A} \) and becomes valid to address the relationship between velocity and cross-sectional area of flow, where \( A \) is the cross-sectional area of the exit nozzle, \( u \) is the gas velocity, and \( M \) is the Mach number. The diverging nozzle causes a continued increase in gas velocity once the flow is sonic at the throat, and the gas velocity in the thruster continues to increase along the expanding divergent nozzle section, resulting in a subsequent rise in thrust. The exhaust gas velocity of a de Laval nozzle \([32]–[34]\) can be calculated from \( u = \sqrt{\frac{TR}{m} \times \frac{2k}{k-1} \times [1 - (\frac{\nu_e}{\nu})^{(k-1)/k}]}, \) where \( T \) is gas temperature, \( m \) is the molecular mass of helium, \( k \) is the specific heat ratio, \( \nu \) is inlet pressure, and \( \nu_e \) is the exit pressure.

**H. SPECIFIC IMPULSE CALCULATION**

From the velocity, specific impulse \( (I_{sp}) \) can be calculated from the equation, \( I_{sp} = \frac{\dot{m}v_e}{\dot{m}} \), where \( \dot{m} \) is the average exhaust speed along the axis of the thruster and \( g \) is the gravitational acceleration at the Earth’s surface. From the thrust, \( I_{sp} \) can be calculated from the equation \( I_{sp} = \frac{T}{\dot{m}g} \), where \( T \) is the thrust and \( \dot{m} \) is the mass flow of the gas.

**IV. CONCLUSION**

In this paper, we detailed our highly beneficial jet-to-jet coupling effect achieved with plasma jet array structures, and an interpretation of the intense plasma mode mechanism. The significance of this effect was successfully demonstrated in a microplasma thruster system that incorporates an array of hollow-core glass fibers that utilize the jet-to-jet coupling effect to produce a marked increase in thrust capacity in both ambient and vacuum conditions at relatively low input power levels of less than 50 W. The microplasma thruster system was further enhanced through the incorporation of a micro-nozzle in the glass fiber to produce a promising microplasma-nozzle effect that combines supersonic gas flow with a strengthened plasma emission. The inherent flexibility and robustness of glass fiber allows for these FPTs to perform in variable environments that require a high freedom of movement, and require minimal payload space for fitting. Thus, these experimental results are expected to be useful in current and future cubesat nanosatellite designs as an innovative low-power method to enhance the thrust characteristics of electric propulsion by utilizing unique phenomenon in plasma science.


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