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INTRODUCTION
Rapid feedback control is needed for practical microwave processing of continuous ceramic oxide filaments to regulate the process temperature where the dielectric properties of the filaments change rapidly with temperature. These dielectric changes can produce large rapid changes in the resonant frequency, the reflectivity, and the power density of the cavity. A broadband traveling wave tube (TWT) amplifier provides a highly versatile process control platform for filament processing. By comparing a RF signal from the cavity to a reference signal from the TWT, phase information can be used in a negative feedback loop to allow the oscillator to track the cavity frequency as it shifts due to the changing dielectric constant in the filaments being heated. By sampling the electric field level in the cavity with a detector, amplitude control can be done to maintain a constant absorbed power in a fiber tow, which is important for controlling the tow heating and temperature. This paper describes the design and testing of feedback controller with mullite rods in a single-mode $TE_{10n}$ resonator driven by a commercial TWT.

ELECTRONIC FEEDBACK CONTROL
The purpose of the electronic control system is to regulate and measure the RF power absorbed by a material placed at an electric-field maximum in a single-mode resonant cavity. The goal is to control the temperature of the fiber during processing. Absorbed power was chosen to be the controlled variable since, in the steady state, constant absorbed power will produce a constant temperature in the fiber. To optimize RF power coupling into the fiber, a frequency control loop was also used to guarantee that the cavity remains on resonance as the fiber tow is heated.

The block diagram in Fig. 1 depicts the design of the frequency control loop. A well established method [1] is used to maintain the resonance condition in the cavity which occurs when the phase of the forward and cavity RF signals differ by $\pi/2$. A mixer is used as a phase detector which produces a DC voltage at its IF port proportional to the phase difference between its RF and LO ports. This voltage is nominally zero when the phase difference $\Delta \phi$ is $\pi/2$. A proportional, integral (PI) controller drives a voltage controlled oscillator (VCO) which shifts the output frequency of the TWT so that $\Delta \phi$ remains at $\pi/2$.

The block diagram in Fig. 2 shows the power control loop. Three crystal detectors (DET) are used to convert the forward ($P_f$), reflected ($P_r$), and cavity ($P_c$) powers to DC voltages. The signals proportional to the reflected and cavity power are then subtracted from the forward power signal. The controller circuit is calibrated to compensate for power losses to the system and cavity. The resulting signal which is proportional to the absorbed power in the fiber tow is subtracted from a set point producing an error signal. A PI controller drives a variable attenuator which modulates the forward power from the TWT so as to reduce the error signal.
EXPERIMENTAL TESTING

The test cavity in Fig. 3 was a TE_{10n} single-mode cavity, consisting of a water-cooled section of copper WR284 waveguide with a coupling iris and “beyond-cutoff” coupler at the inlet and an adjustable short [2-3]. The test cavity was tuned to operate near 3 GHz. The cavity was fabricated with two pairs of opposing circular ports, as shown in Fig. 4, positioned at an electric field maximum. Test samples were loaded through the paired ports aligned with the transverse electric field in the cavity. The pair of ports, perpendicular to the transverse electric field in Fig. 4, provided for insertion of an Accufiber optical fiber thermometer (OFT) and for video recording of the heated sample. The OFT unit had a dual-wavelength module and a lightpipe sensor to measure the mean sample temperature [2]. The ratio temperatures reported in this paper are two-color temperatures computed from the ratio of light intensities measured at 800 nm and 950 nm.

The feedback controller was tested by microwave heating stationary and moving test samples to examine the ability of the controller to regulate the sample temperature. The test sample was a mullite rod with a 3-mm diameter. Temperature control by the feedback controller was...
compared to that by manual control. Feedback controlled heating was performed with the feedback controllers outlined in Figs. 1 and 2 with rapid continual adjustment in the resonant frequency and TWT power. Manual heating conditions were set by manual control of the TWT frequency and power through a sweep generator (VCO). Manual control consisted of heating at a fixed frequency and output power from the TWT set at the beginning of the test.

TESTING RESULTS
Fig. 5 contrasts the time-temperature response of stationary mullite rod for feedback controlled and manually controlled heating at 2.93 GHz. As seen in Fig. 5, the rod temperature under manual control drifted continually to lower values after heating the rod to temperature. The rod temperature under feedback control was very steady with a small drift over 8°C. Under manual control the forward power was quite steady, but the reflected increased continually under heating.

Fig. 6 shows the temperature-time response under manual control for a heated mullite rod that was pulled through the cavity at ~4 mm/min after stationary heating for 10 to 15 minutes. The measured temperature of the moving tow varied strongly with large changes over a 78°C range. Surprisingly, feedback controlled heating also yielded large changes in measured temperature over a 68°C range. Under controlled heating, the change in rod temperature was gradual without rapid swings, but still larger than the desired ±10°C range. Similar experiments with moving NICALON tows [3] indicated no significant temperature control for feedback controlled over manual controlled heating.

![Fig. 4. Cross-sectional view of the TE10n cavity, showing the rod position with OFT temperature sensor and video camera.](image)

![Fig. 5. Mean temperature versus time for stationary mullite rod under feedback controlled heating and manual heating at 2.93 GHz.](image)

![Fig. 6. Mean temperature versus time for a moving mullite rod under feedback controlled heating and manual heating at 2.93 GHz. Start of pulling indicated by arrows.](image)
Video recordings of the heated rod showed that intense heating occurred only over a ~5-mm length of entire 34-mm rod length in the cavity. Because only a short segment of the rod was heating strongly, there is a possibility that part of measured temperature variations in Fig. 6 maybe an artifact of the temperature measurement. Video recordings showed that the heated zone on the moving rod held a steady position relative to OFT sensor with only small changes in position of ±1 mm, or less. The OFT sensor viewed a 5 to 6 mm segment of the mullite rod and measured a mean temperature for the viewed segment. Any movement of heated zone in or out of view by the OFT sensor could potentially induce a change in the measured mean temperature without an actual change occurring. Such heated zone movement caused large fluctuations of 200°-300°C in the measured temperature for moving NICALON tows [3]. Effect of heated zone movement on the rod temperature measurement was certainly reduced in the rod experiments, but perhaps not eliminated. Further testing of this feedback control scheme will continue to eliminate the fluctuations in the temperature measurement.

CONCLUSION
A feedback control system was designed to work with a TWT to regulate the temperature of a stationary and moving filament tow as heated in a single-mode resonant cavity. The control system simultaneously maintains the TWT frequency at resonance and the microwave power absorbed in the tow at a desired level. The feedback control was tested with a TE10n single-mode cavity for microwave heating of 3-mm mullite rods. Temperature control was quite satisfactory for stationary mullite rod, but not so for moving mullite rods. Tests with moving mullite rods may still be obscured by measurement fluctuations in the mean sample temperature.

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REFERENCES