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Development of plasma bolometers using fiber-optic temperature sensors

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Measurements of radiated power in magnetically confined plasmas are important for exhaust studies in present experiments and expected to be a critical diagnostic for future fusion reactors. Resistive bolometer sensors have long been utilized in tokamaks and helical devices but suffer from electromagnetic interference (EMI). Results are shown from initial testing of a new bolometer concept based on fiber-optic temperature sensor technology. A small, 80 μm diameter, 200 μm long silicon pillar attached to the end of a single mode fiber-optic cable acts as a Fabry-Pérot cavity when broadband light, $\lambda_0 \sim 1550$ nm, is transmitted along the fiber. Changes in temperature alter the optical path length of the cavity primarily through the thermo-optic effect, resulting in a shift of fringes reflected from the pillar detected using an I-MON 512 OEM spectrometer. While initially designed for use in liquids, this sensor has ideal properties for use as a plasma bolometer: a time constant, in air, of ~ 150 ms, strong absorption in the spectral range of plasma emission, immunity to local EMI, and the ability to measure changes in temperature remotely. Its compact design offers unique opportunities for integration into the vacuum environment in places unsuitable for a resistive bolometer. Using a variable focus 5 mW, 405 nm, modulating laser, the signal to noise ratio versus power density of various bolometer technologies are directly compared, estimating the noise equivalent power density (NEPD). Present tests show the fiber-optic bolometer to have NEPD of 5-10 W/m² when compared to those of the resistive bolometer which can achieve <0.5 W/m² in the laboratory, but this can degrade to 1-2 W/m² or worse when installed on a tokamak. Concepts are discussed to improve the signal to noise ratio of this new fiber-optic bolometer by reducing the pillar height and adding thin metallic coatings, along with improving the spectral resolution of the interrogator. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4960421>]

I. INTRODUCTION

Measuring and understanding power loss channels is an important consideration for many plasma systems, from plasma processing to magnetically confined fusion (MCF) plasmas. Recent experimental work on tokamaks has focused on the development of radiative exhaust scenarios which convert power normally conducted to surfaces on open field lines to isotropic photon emission helping to avoid heat flux limits of plasma facing components. Empirical and theoretical progress is enabled by bolometers which can measure spatially resolved radiated power flux. Typically, resistive bolometers¹ (RBs) are used in pinhole cameras, which infer the power flux along collimated lines of sight through the plasma by measuring the temperature change of an absorber via the change of resistance of a thermally connected meander. More recently infrared video bolometers (IRVBs) have been developed which measure the absorber's temperature change

by using IR thermography.² This work presents research and development of a new type of bolometer which uses fiber-optic temperature sensing based on an existing Fabry-Pérot design,³ combining the absorber and the sensor into single compact, ~ 200 μm , unit. The initial fiber-optic bolometer (FOB) is demonstrated to have a noise equivalent power density (NEPD) of 5-10 W/m², with NEPD defined to be the power flux into the sensor at which signal to noise is unity. The FOB NEPD is presently worse than resistive bolometers on the bench, <0.5 W/m², although both RB's deployed in MCF devices and IRVB are found to be ~ 1 -2 W/m². Near term R&D indicates that the FOB can be made to meet or improve upon the NEPD of the benchtop RB, opening up the possibly for new research pathways.

Achieving lower NEPD is the key metric for increasing the spatial resolution of bolometers as the sensors are deployed in pinhole cameras and cannot use refractive or reflective focusing optics. Power density from the plasma at the sensor, P_{det}/A_{det} , is

$$\frac{P_{det}}{A_{det}} = \frac{A_{ap}}{4\pi l^2} Br,$$

where A_{ap} is the area of the aperture, l is the aperture detector distance, and Br is the line-integrated brightness from the

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plasma. Maintaining optimal spatial resolution limits $A_{ap} \sim A_{det}$ and fixes $l/A_{det}^{1/2}$ to be the same between the sensors of different sizes. Thus the power density at the detector of two pinhole cameras with two different sensors will be the same, assuming that they have the same spatial resolution, i.e., a smaller sensor has a smaller aperture but is located closer to the pinhole. While a smaller sensor may enable a more compact design, it would see the same power flux; thus making the ability to resolve spatio-temporal evolution a matter ensuring measured power density is some multiple above the NEPD. This makes comparisons of NEPD between different bolometers a key metric for choosing between technologies.

Section II of this work introduces the concept of fiber-optic temperature sensing, possible benefits for its use as a plasma bolometer, and which existing sensor approaches are most applicable to the bolometer role. Section III describes initial testing of a Fabry-Pérot temperature sensor designed for its use in liquids at the University of Nebraska-Lincoln, and Section IV details ways that the NEPD can be reduced through changes in sensor construction and utilization of an improved interrogator.

II. FIBER-OPTIC TEMPERATURE SENSING (FOTS) FOR MCF PLASMA DEVICES

Fiber-optic temperature sensing (FOTS) is a mature measurement technique widely used in research and industrial applications.^{4,5} This relies on imbedding, attaching, or encoding a resonant interaction region to a fiber-optic cable, where local environmental changes leave a response on reflected or transmitted light carried by the fiber-optic cable. Fiber Bragg Gratings (FBGs) create a periodic index of refraction change in the fiber core, leading to a single peak (valley) in reflected (transmitted) light. The central wavelength shifts as the FBG is modified due to strain or temperature and sensitivity is quoted in wavelength shift per degree, which for FBGs is ~ 10 pm/°C. FOTS is an active technique, and near infrared light is typically utilized, allowing telecommunication technology to be used in sending and receiving light. A primary advantage of FOTS is the inherent immunity to electrical magnetic interference since the response is measured remotely, 100's to 1000's of meters, from the sensor. This makes it an ideal technology to attempt to exploit in magnetic confinement fusion where magnet and heating systems are the known sources of noise on bolometers⁶ and thermocouples. While seeing isolated use as temperature and strain sensing ex-vessel systems, there appears to be only limited use in-vessel at this time.⁷ Applications for noise-immune calorimeters should be feasible with present technology and should be pursued, while as shown in Section III, the use of FOTS for bolometry requires further development. An ultimate limitation of any fiber-optic temperature sensing approach in D-T or long-pulse D-D MCF devices will likely be the “darkening” of fiber-optic cable.⁸ It is worth noting that active nature of FOTS means that the input light source can be increased in brightness to offset any initial attenuation or radioluminescence, meaning that present successful use of *in vacuo* fibers for optical systems indicates that the FOTS technology can be utilized in existing devices.

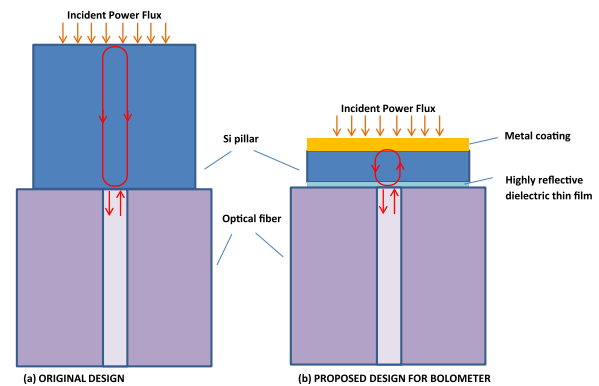


FIG. 1. Schematic of the Fabry-Pérot based fiber optic bolometer with the original design (a) and the proposed upgrade to reduce the NEPD (b).

Surveying possible fiber-optic temperature sensors revealed many are ill-suited for a role as a bolometer that would be competitive to RB or IRVB. For example, FBGs are low-cost and can be deployed in multi-channel arrays, but the sensing portion is buried within the fiber core, requiring heat from plasma radiant power flux to conduct through the fiber cladding, ~ 100 μm before it can be conducted axially away from the FBG. Thus, there is little increase in temperature due to heat transport, which combined with the low sensitivity of the FBG, and the modest resolution of standard interrogators, ~ 1 pm, results in a high NEPD. While this may not be usable as a sensor for spatially resolved radiation measurements, it could see use as a measure of average wall power flux in recessed areas to aid global power balance studies.

An existing design of a sensor based on a Fabry-Pérot cavity has an ideal geometry for use as a plasma bolometer.³ This uses a small, 80 μm diameter, 200 μm long Si pillar attached to the free end of a fiber-optic cable with a UV-curable adhesive, shown schematically in Figure 1(a). The power flux from the plasma radiation can be made to fall directly on the sensor and then be conducted to the fiber with a time constant of ~ 100 -200 ms. To measure the change in temperature, a white light source is input into the fiber, where the Si pillar creates the typical interferogram response of a Fabry-Pérot cavity. This results in multiple peaks, in contrast to one from an FBG, where the central wavelength shifts as the optical path length is varied, primarily due to the temperature sensitivity of the index of refraction of Si, but also the thermal expansion of the pillar itself. The cantilevered design is stress free, avoiding any thermal-strain contribution to the sensor response. Simultaneously measuring multiple peaks from the Fabry-Pérot cavity spectrometer allows a reduction of the uncertainty in the change in temperature. A sensitivity of 84.6 pm/°C has been previously demonstrated.

III. INITIAL LABORATORY TESTING

The sensor described in Ref. 3 was examined in more detail in the environment and configuration which would be expected when using it as a fiber-optic bolometer. The physical construction was tested in a vacuum chamber, where the fiber/pillar unit survived bake-out at 250-300 °C for approxi-

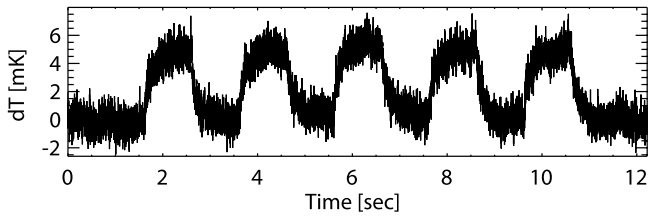


FIG. 2. Time history of the change in temperature of the fiber-optic bolometer, exposed to a 0.5 Hz square wave power flux at $\sim 40 \text{ W/m}^2$.

mately one day without mechanical failure. In-air laboratory, tests were conducted to test the noise equivalent power density. A $\sim 5 \text{ mW}$ Global Laser BlueLyte diode laser was used to expose the FOB to a power flux at 405 nm of $5.0\text{--}70 \text{ W/m}^2$, measured using a Thorlabs PDA36A. A 0.5 Hz square wave was used to modulate the laser, while observing the response of the $200 \mu\text{m}$ high, $80 \mu\text{m}$ diameter Si pillar acting as Fabry-Pérot cavity. A white light source was used along with an I-MON 512 OEM spectrometer to measure interferogram fringe shifts, interpreted into temperature changes using the same process as described in Ref. 3. The resulting change in temperature relative to $t = 0$ is shown in Figure 2 for $\sim 40 \text{ W/m}^2$ of input power. A baseline drift of $< 2 \text{ mK}$ has been accounted for assuming a linear evolution. In contrast, resistive bolometers have designed in compensation for such an environmental temperature change by using active and passive sensors in Wheatstone bridge configuration. Future tests will try co-locating active and blind FOB sensors to account for environmental drift. The signal to noise is computed by dividing the change in temperature by $\sqrt{2}\sigma_T$ where σ_T is the standard deviation of the observed signal. Looking at the noise spectrum, there is no coherent structure indicating the noise is limited by random measurement error. The signal to noise ratio (SNR) is plotted versus laser power density in Figure 3, where the SNR crosses unity between 5 and 10 W/m^2 , which is taken to be the noise equivalent power density. Similar benchtop tests were also completed for a resistive bolometer of the type in Ref. 1 along with an estimate of signal to noise ratio (SNR) for a resistive bolometer deployed at Alcator C-Mod. These are also plotted for comparison in Figure 3 where the bench-top RB sensor has an NEPD $< 0.5 \text{ W/m}^2$, while the RB sensor

deployed on the tokamak is $\sim 1\text{--}2 \text{ W/m}^2$. Poor absorption of RF power can increase this further; for example, the NEPD of Alcator C-Mod RB's can reach up to $> 100 \text{ W/m}^2$ if ICRF has low single pass absorption.

IV. FUTURE WORK

The initial tests in Section III indicate that the Fabry-Pérot temperature sensor does not yet have a sufficiently low NEPD to replace conventional resistive bolometers. But, with NEPD of $5\text{--}10 \text{ W/m}^2$, targeted use where its compact size and resistance to electromagnetic interference (EMI) would present an advantage could be envisioned. To drop the NEPD further, an improved FOB will be constructed by reducing the height of the silicon pillar, resulting in an increased temperature change. Reduction of pillar sizes to below $115 \mu\text{m}$ results in transmission of soft x-rays that exceed that of a standard RB, but this can be ameliorated by the addition of a thin, metallic absorber layer on the plasma-facing side of the pillar. While this increases the thermal mass of the system, there is a net gain in ΔT for a fixed input power flux because the size of the Si pillar can be more strongly reduced. Figure 4 shows the increase in temperature expected for a 1 W/m^2 input power flux for a FOB with varying Au coating thickness and Si pillar height while maintaining a fixed 20% transmission for photons at 8 keV, similar to presently used resistive bolometers. This is calculated assuming a lumped thermal mass with a combined $\rho c_p V$, where heat is perfectly shared between the Au coating and the pillar and $\Delta T = qA\tau/(\rho c_p V)$. Here, q is the heat flux on the flat face of the pillar with area, A , and a time constant, τ , of 100 ms is assumed. In this case, zero thickness Au corresponds to $112 \mu\text{m}$ Si and $3.5 \mu\text{m}$ Au corresponds to $13 \mu\text{m}$ Si. Note that for the $200 \mu\text{m}$ pillar discussed in Section III, this estimate would predict a $\Delta T \sim 7 \text{ mK}$ for $q = 40 \text{ W/m}^2$ assuming a 55% absorption coefficient (for 405 nm light), in rough agreement with Figure 2. This suggests a factor of 5-10 increase in ΔT , with an equivalent drop in NEPD, is feasible by moving beyond the present uncoated design used in Section III. It remains to be seen how thin the Si pillar can be made without negatively impacting its role as a Fabry-Pérot cavity.

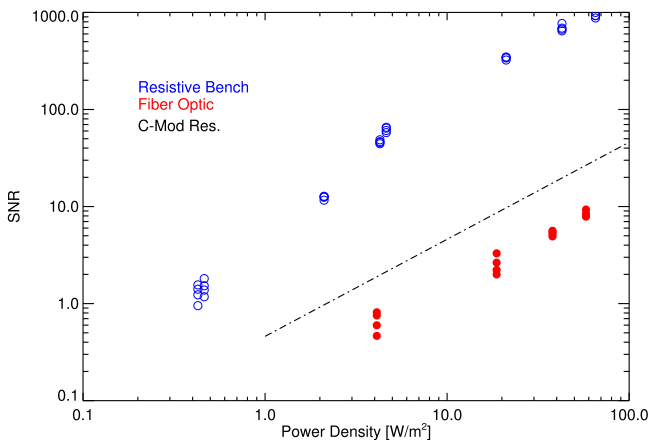


FIG. 3. Measured signal to noise ratio (SNR) versus power density for various bolometer sensors.

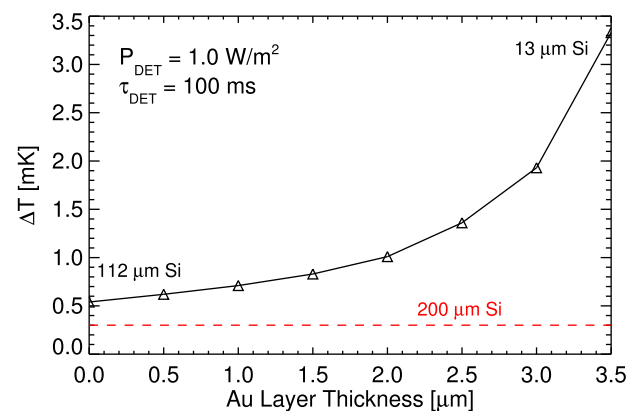


FIG. 4. Calculated effect of adding an increasing layer of Au and reducing the length of the Si pillar to keep the transmission of 8 keV photons to 0.2.

Further improvement in the NEPD is possible by improving the resolution of interrogator. The σ_T is driven by the resolvable wavelength shift. Free-space optics spectroscopy used in Section III has a resolution of ~ 100 fm. Further reduction is thought to be possible by using an integrated photonics interrogator developed by Technobis. The Ladygator⁹ series of instruments utilizes independent wavelength scanning lasers to probe the sensor and an arrayed waveguide grating to analyze its response. While the existing design uses multiple lasers to simultaneously track multiple FBGs with high resolution, it is thought that this interrogator can be adapted to simultaneously examine multiple peaks of the Fabry–Pérot temperature sensor. An initial prototype is under development for testing with the FOB with an expectation of reaching a $\Delta\lambda \sim 20$ fm. Combining this with the NEPD reduction through changing the pillar design, a reduction of up to 50 is estimated to be possible which would result in the NEPD reaching that of the resistive bolometer on the bench, shown in Figure 3. Due to inherent insensitivity to EMI, a FOB deployed on an MCF device may end up with better signal to noise than could be achieved using RB or IRVB.

Much remains to be tested and confirmed before the FOB could be considered a useful replacement or complement to existing bolometer technologies. New prototypes will be tested

on the bench and on plasma devices in the next two years, where direct comparison to resistive bolometers will be made to isolate any NEPD advantages. While initial tests will probe the ultimate NEPD achievable, considerations on the cost-per-channel will also need to be kept in mind as sensors need to be deployed in arrays of order 100 to enable cost-effective tomographic inversions.

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