Electrical-Substitution Fourier Transform Spectrometry for Absolute Calibration of Detector Responsivity

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We have developed a generalized method for electrical substitution which can operate at time constants compatible with continuous-scan Fourier transform spectrometry, and have applied the method successfully to measure absolute detector spectral responsivity from 1.5 µm to 11 µm. For this project we have also fabricated and characterized a carbon-nanotube planar bolometric radiometer optimized for this application. When combined, the new electrical-substitution electronics and radiometer could provide high-resolution absolute spectral responsivity from 1.5 µm to 50 µm, calibrated directly against a primary standard detector.

INTRODUCTION

Absolute cryogenic radiometers (ACRs) are the basis for most detector-based optical power scale realizations, but these electrical-substitution (ES) primary standards are typically slow ($\tau > 1$ s) and of limited use for spectral calibrations. Cryogenic ES bolometers can be significantly faster [1,2] and the ES method can be generalized beyond shuttered measurements [3], so it is possible to realize a much more versatile and higher-speed ACR. These primary standard detectors can exploit the inherent noise advantage of AC measurements and can be coupled with continuous-scan Fourier transform spectrometers (FTS) for absolute spectral calibrations.

We have developed electronics for electrical-substitution-with-FTS (ES-FTS) and a new planar bolometric radiometer (PBR) with an absorber made from vertically-aligned carbon nanotubes (VACNTs). The electronics and related firmware can actively control the temperature of a bolometer experiencing any periodic optical signal, and the PBR has a time constant of around 10 ms. We have developed the ES-FTS method and verified the function of the electronics with a test ES bolometer (ESB) [1], while fabricating the new PBR in parallel.

The first application for the ES-FTS primary standard radiometer is for a detector comparator instrument which can measure absolute spectral responsivity of a detector-under-test (DUT) against the ACR. We have built-up and tested such an ES-FTS detector comparator using a commercial FTS and our electronics.

ES-FTS PROCEDURES AND ELECTRONICS

The layout for our ES-FTS detector comparator is shown in Figure 1. Both the high-speed ACR and the DUT measure the same beam from the FTS, which can be focused (f/8) onto either detector with a parabolic mirror on a rotation stage. The electrical substitution can "keep up" with the metrology signals from the FTS when operating at a 100 Hz scan rate in continuous-scan mode.

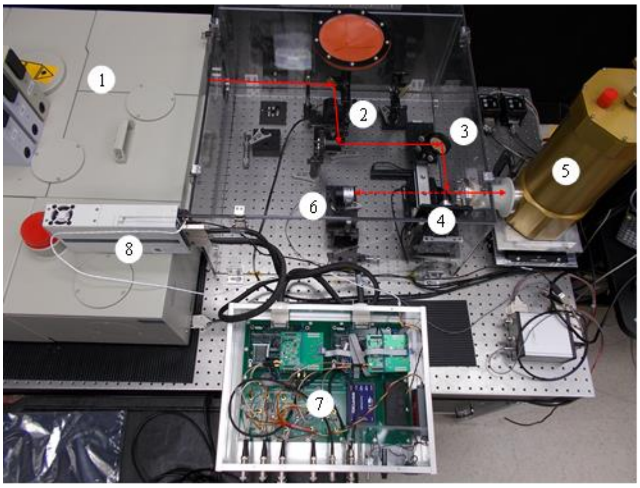

Figure 1. Spectral comparator layout with the following labeled components: 1) FTS, 2) spatial filter, 3) fold mirror, 4) rotating paraboloid, 5) ACR, 6) DUT, 7) ES-FTS electronics, and 8) FPGA.

In typical "DC" electrical substitution an ACR is temperature-controlled while opening and closing a shutter in front of the beam: the extra heat required to maintain the temperature with shutter closed is equivalent to the optical power. Generalized electrical substitution depends on determining the electrical heating waveform which must be applied to the ACR heater in sync with the interferometric optical signal in order to achieve net AC signal near zero from the

ACR thermistor. The governing relation for the ACR thermistor resistance is very similar to standard FTS relations, with the optical spectrum $B(\nu)$ replaced by $B(\nu)\cdot G(\nu)$, where $G(\nu)$ is the complex response (including gain and delays) of the ACR resistance. For a well-made ACR, there is an equivalence between applied optical and electrical power, and the governing relation is identical whether $B(\nu)$ represents the optical or electrical spectrum.

Determination of the required feedback function is made according to the following procedure: first, $G(\nu)$ is estimated by measuring ACR thermistor response to a known electrical heater waveform; second, the estimated $G(\nu)$ is used to calculate the heater waveform required to cancel the measured optical signal; third, this feedback is applied to cancel the optical pulse; then, all these steps are iterated starting from the remainder signal achieved in the third step. Multiple iterations are required to achieve good cancellation because ACR thermistor response as a function of power is not generally linear, but no more than 3 iterations are usually required to achieve cancellation > 99 %. Figure 2 is an example of successful cancellation of the ESB signal. After cancellation is achieved, the small leftover portion is averaged over many scans and quantified along with the electrical feedback power required to cancel the optical signal.

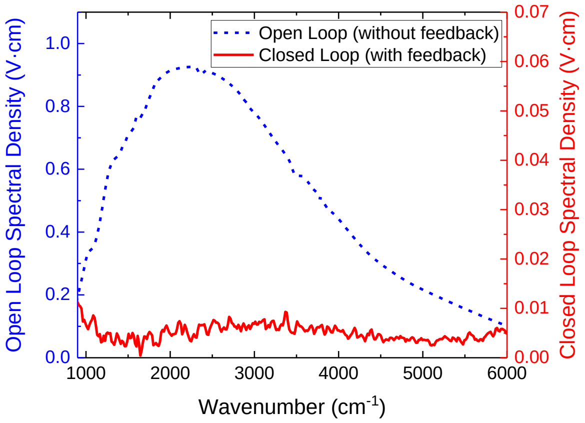

Figure 2. Open and closed loop data for an ES-FTS measurement with the ESB detector, showing > 99 % cancellation by feedback in the closed loop case.

The digital acquisition and feedback are controlled by a commercial field-programmable gate array (FPGA). Timing metrology signals fed from the FTS to the FPGA are used to sync the electrical and optical measurements. Seven channels of analog-to-digital input to the FPGA include: 2 channels for FTS metrology, one for the ACR thermistor, 3 for the ACR heater, and one for the DUT. One channel of digital-to-analog output sends the feedback signal to the ACR heater.

HIGH-SPEED ES DETECTORS

We have successfully tested our generalized ES method and electronics with a gold-black ESB detector [1], while developing an optimized carbon-nanotube PBR in parallel. The ESB AC response has a 3 dB point (1/2 of max signal) at about 30 Hz, and the gold-black coating provides near-unity absorption out to around 12 µm. Used in a cryostat with a BaF_2 window, it can serve as an ACR over the spectral range from 1.5 µm to 11 µm. The PBR (which is shown in Figure 3) has been fabricated and characterized, and exhibits AC response with a 3 dB point at about 100 Hz. The vertically-aligned carbon nanotubes provide near-unity absorption out to 50 µm, and in a cryostat with a CsI window the PBR is expected to serve as a high-speed ACR from 1.5 µm to 50 µm.

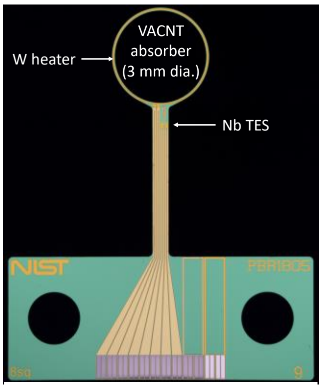

Figure 3. Photo of PBR.

CONCLUSIONS AND SUMMARY

The ES-FTS method and electronics have been demonstrated, and we have developed a fast carbon nanotube PBR optimized for absolute spectral measurements with an FTS. The ES-FTS method has been applied to a detector spectral responsivity instrument, which can provide absolute spectral responsivity from direct comparison with an optical power primary standard detector. The last step of the project will be to operate the new PBR in ES-FTS mode, and to intercompare its measurements with those of legacy ACRs.

REFERENCES

1. J.P. Rice, An electrically substituted bolometer as a transfer-standard detector, Metrologia, 37, 433-436, 2000.
2. N.A. Tomlin, M. White, I. Vayshenker, S.I. Woods, J.H. Lehman, Planar electrical-substitution carbon nanotube cryogenic radiometer, Metrologia 52, 376–383, 2015.
3. C.A. Hamilton, G.W. Day, R.J. Phelan, Jr., An electrically calibrated pyroelectric radiometer system, NBS Technical Note 678, National Bureau of Standards, 1976.