PICOSECOND DUAL-SOURCE INTERFEROMETER EXTENDING FOURIER-TRANSFORM SPECTROMETER TO MICROWAVE REGIME

D. W. van der Weide† and F. Keilmann‡

† Department of Electrical Engineering
University of Delaware
140 Evans Hall
Newark, DE 19716-3130 USA
dan@eecis.udel.edu

‡ Max-Planck-Institut für Biochemie
Abt. Molekulare Strukturbiologie
82152 Martinsried GERMANY

keilmann@alf.biochem.mpg.de

ABSTRACT

We report a dual-source interferometer based on nonlinear transmission lines and integrated antennas which interfaces directly with a Fourier-transform infrared (FTIR) spectrometer to enable longer-wavelength measurements than normally possible with a black-body source. As a demonstration, we show preliminary transmission measurements through a plate of high-resistivity silicon.

INTRODUCTION

Fourier-transform infrared (FTIR) spectroscopy is the dominant method for measuring near- and far-infrared transmission phenomena[1]. While this technique is employed to accurately measure solids in the millimeter-wave regime with specialized equipment[2], the relative weakness of the black-body source (usually a mercury vapor arc lamp) below 10 cm^{-1} (300 GHz) requires prohibitively long scans and averaging times for many measurements. Interesting physical phenomena lie in this region, however, and workers studying, for example, the energy-gap distribution in high-T_c superconducting thin films have used different techniques to access this spectral regime[3-5] with varying degrees of success.

In this work, we present a new and potentially superior method of extending the response of a common FTIR spectrometer from 300 GHz down to the low microwave (~ 10 GHz) regime through the simple addition of another source which is much "brighter" than a typical black-body in this regime. By spatially combining the freely-propagating beams from two coherent picosecond pulse generators (which have discrete Fourier spectra ranging from 10–450 GHz), we have developed a compact, reliable, and easy-to-implement long-wavelength extension for an FTIR spectrometer. Because this dual-source interferometer modulates each harmonic of one source with a precisely-offset harmonic from the other source, the resultant beat frequency can be low enough for detection by a standard composite bolometer, hence the same detector is used for both the black-body and the new dual source.

We demonstrate this method by measuring the transmission of a high-resistivity silicon plate using both sources and comparing the data in the spectral regime where they overlap. While our data are distorted by standing-wave effects, the results are clear enough to warrant further investigation, and it is clear that careful alignment and use of microwave absorbing materials on the interior walls of the spectrometer would substantially improve the measurements.

DUAL-SOURCE INTERFEROMETER

TH 3F

To generate the broadband (discrete) spectral energy for this application, we use nonlinear transmission line (NLTL) pulse generators coupled to broadband planar antennas. The

0-7803-3246-6/96/$5.00 © IEEE

1996 IEEE MTT-S Digest

GaAs IC NLTLs used in this work consist of series inductors (or sections of high-impedance transmission line) with varactor diodes periodically placed as shunt elements. On this structure at room temperature a fast (~ 2 ps) voltage step develops from a sinusoidal input because the propagation velocity u is modulated by the diode capacitance, $u(V) = 1/\sqrt{LC(V)}$, where L is the line inductance and $C(V)$ the sum of the diode and parasitic line capacitance. Limitations of the NLTL arise from its periodic cutoff frequency, waveguide dispersion, interconnect metallization losses, and diode resistive losses. Recent improvements in NLTL design have resulted in sub-picosecond pulses at room temperature[6] but these circuits have not yet been employed in this version of the dual source.

In the dual-source interferometer, the output of each NLTL feeds an integrated bow-tie antenna mounted at the focus of a hyperhemispherical high-resistivity silicon lens[7]. These lenses in turn are mounted at the foci of off-axis paraboloidal mirrors (see Fig. 1). The beams collimated by the mirrors are either transmitted (Source "A") or reflected (Source "B") by a wire-grid polarizing beamsplitter. Each beam then contributes equally to the final, linearly-polarized beam by arrangement of a final wire-grid polarizer mounted at 45 degrees to the beamsplitter (Fig. 1). Note that, while the prototype construction is already small (~ 170 mm long, 120 mm wide, and 80 mm high), it would be possible to fabricate two antennas and their circuitry on the same substrate, making the whole system extremely compact[8]. We also note that other workers have described similar ideas using laser-triggered photoconductive switches[9-11].

Each source is fed by a 100–500 mW sinewave generated by one of two microwave synthesizers, both of which share a common timebase. The output of one synthesizer is offset by $\Delta f << f_0$ ($\Delta f \sim 100$ Hz; $f_0 \sim 10$ GHz), and this offset is used as a trigger for a Fast-Fourier-Transform (FFT) spectrum analyzer. While the synthesizers and broadband power amplifiers used in the present demonstration are expensive (total cost ~ US$80,000), they could readily be replaced by fixed-frequency high-power sources, although the synthesizers provide the advantage of precise (1 Hz) tuning of the output harmonics.

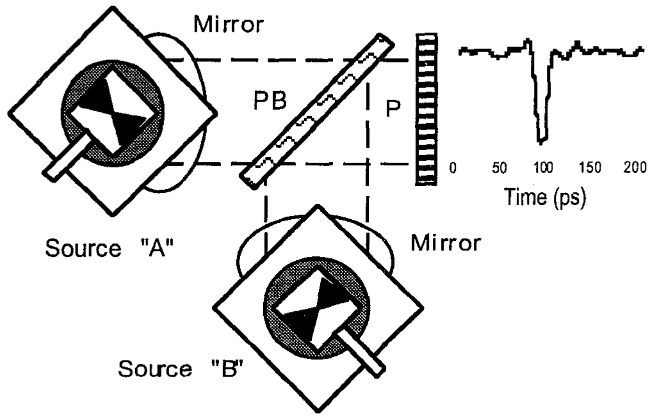

Figure 1. Dual-source interferometer configuration. Each source antenna is at the focus of a paraboloidal mirror and radiates a polarized beam, which is transmitted ("A") or reflected ("B") by the polarizing beamsplitter (PB). The output polarizer (P) selects half the power of each beam. The output waveform as detected by a bolometer is shown.

DESCRIPTION OF EXPERIMENT

We situated the dual-source interferometer inside a Bruker 113-V FTIR spectrometer as shown in Fig. 2. An off-axis paraboloidal mirror was used to turn and focus the beam onto a 20 mm diameter, 1.012 mm thick plate of ~ 50 kΩ cm silicon held in a 10 mm diameter iris. We measured the transmittance of the plate using the arc lamp of the 113-V down to 10 wavenumbers, below which the signal-to-noise ratio of the instrument degrades to less than the modulation depth of the plate transmittance (solid line in Fig. 3 for a measurement time of ~ 10 minutes).

We then a turning mirror ("M" in Fig. 3) to direct the output of the dual-source through the sample, with alignment made possible by observing the interferogram (Fig. 1) on an oscilloscope; much better alignment could be achieved by using a guide laser. We used no absorbers or attenuators for reducing reflections or standing waves[12], so the spectra measured below 5 cm^{-1} (150 GHz) show correspondingly strong evidence of these effects as well as of diffraction, although their repeatability was very good. The output of the bolometer was Fourier-transformed in real-time (averaged over ~ 2 min), and is shown compared to the FTIR data and a theoretical simulation neglecting losses in Fig. 3.

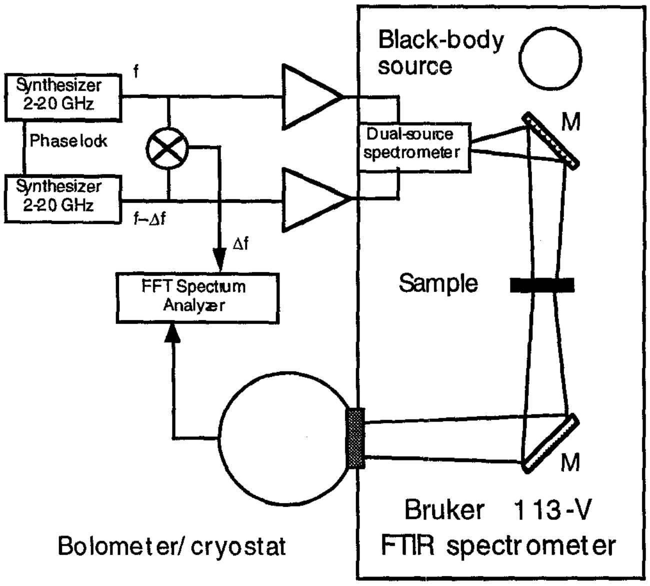

Figure 2. Experimental setup: Dual-source interferometer pumped by phase-locked microwave synthesizers at f ~ 10 GHz. The offset frequency Δf ~ 100 Hz is taken as the trigger signal to the FFT spectrum analyzer and represents the frequency of the microwave fundamental.

DISCUSSION OF RESULTS

As can be seen in the data of Fig. 3, there is a good but not excellent correspondence between the data taken with the two techniques, and this is likely due to the standing-wave and diffraction effects mentioned above; the 10 mm iris sample holder definitely rules out repeatable transmission below 1 cm^{-1} (30 GHz). We also note that the fit to the calculation of transmittance neglecting losses is better in the higher-wavenumber regime when assuming $\varepsilon_r = 12.4$, while at longer wavelengths a better fit is with $\varepsilon_r = 11.5$, where ε_r is the permittivity relative to free-space. This may be due to dispersion of free carriers in the silicon; its resistivity was measured at DC.

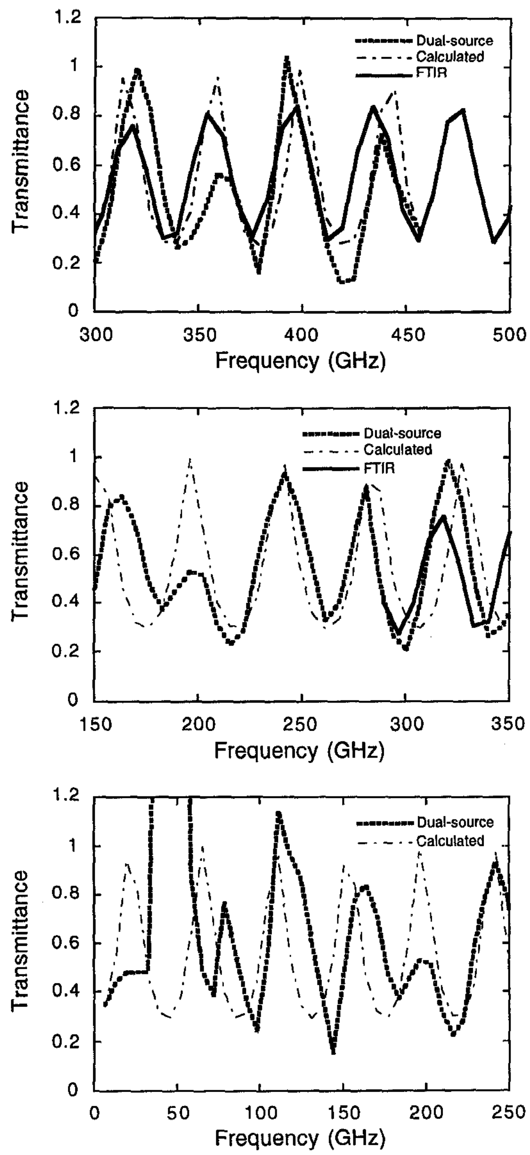

Figure 3. Measured transmittance through a high-resistivity Si plate using FTIR black-body source and dual-source spectrometer. Upper calculation assumes $\varepsilon_r = 12.4$, while lower calculations assume $\varepsilon_r = 11.5$; neither calculation includes loss or dispersion. Data from dual source are shown smoothed and connected as a guide to the eye.

It is worthwhile to briefly compare this new source to a black body. The main difference from the FTIR perspective is that the new source emits a discrete spectrum having its power concentrated in harmonically-spaced lines with extremely narrow width (typically < 100 Hz at a 300 GHz harmonic). By contrast, the thermal source has a continuous emission spectrum, so to compare their "brightness" or power per line requires a choice of measurement bandwidth. Bostak[13] treats this comparison in some detail, so we merely summarize here: For a 900° K black-body source of 1 cm^2 area at 300 GHz, 7.5 nW are radiated in a 1 GHz bandwidth. We measure for the dual-source ~ 200 pW at 300 GHz, but this is concentrated in a < 100 Hz bandwidth, so as the instrumental width gets narrower, the dual-source interferometer grow comparatively brighter than the black-body; the FTIR bandwidth must be 30 MHz for equivalence. Since the individual lines from the dual source can be tuned with 1 Hz resolution, our approach is particularly attractive for measuring narrow-band or high-Q phenomena.

SUMMARY/CONCLUSIONS

In conclusion, we have described and demonstrated a new technique for extending the response of a common FTIR spectrometer into the microwave regime by adding a new interferometer having no moving parts but rather one whose phase is controlled electronically via a frequency offset between its two identical sources. This dual-source interferometer can be readily incorporated into most FTIR spectrometers directly, and promises to enable more complete and accurate broadband phenomena.

ACKNOWLEDGMENTS

Thanks are due to W. König and J. Kuhl (Max-Plank-Institut für Festkörperforschung, Stuttgart) and to J. Bostak and D. M. Bloom (Stanford University) for support and helpful discussions.

REFERENCES

[1] G. W. Chantry, *Long-wave Optics*, Vol. 1. London: Academic Press, 1984.

[2] M. N. Afsar, "Dielectric measurements of millimeter-wave materials," *IEEE Transactions on Microwave Theory and Techniques*, vol. 32, pp. 1598-1609, 1984.

[3] M. C. Nuss, K. W. Goossen, J. P. Gordon, P. M. Mankiewich, M. L. O'Malley, and M. Bhusan, "Terahertz time-domain measurement of the conductivity and superconducting band gap in niobium," *Journal of Applied Physics*, vol. 70, pp. 2238-2241, 1991.

[4] D. Miller, P. L. Richards, E. J. Nicol, E. S. Hellman, E. H. Hartford, Jr., C. E. Platt, R. A. Schweinfurth, D. J. VanHarlingen, and J. Amano, "Direct submillimeter absorptivity measurements on epitaxial $Ba_{1-x}K_xBiO_3$ films at 2 K," *Journal of the Physics and Chemistry of Solids*, vol. 54, pp. 1323-6, 1993.

[5] D. Miller, P. L. Richards, and P. Merchant, "Magnetic-field effects on submillimeter absorptivity in epitaxial thin films of $YBa_2Cu_3O_7$," *Physical Review B (Condensed Matter)*, vol. 51, pp. 8385-9, 1995.

[6] D. W. van der Weide, "Delta-doped Schottky diode nonlinear transmission lines for 480-fs, 3.5-V transients," *Applied Physics Letters*, vol. 65, pp. 881-883, 1994.

[7] D. W. van der Weide, "Planar antennas for all-electronic THz systems," *Journal of the Optical Society of America B*, vol. 11, pp. 2553-2560, 1994.

[8] D. W. van der Weide and F. Keilmann, "Spectrometer using coherent waves," U.S. and German Patent Pending, 1994–95.

[9] B. I. Greene, J. F. Federici, D. R. Dykaar, R. R. Jones, and P. H. Bucksbaum, "Interferometric characterization of 160 fs far-infrared light pulses," *Applied Physics Letters*, vol. 59, pp. 893-895, 1991.

[10] S. E. Ralph and D. Grischkowsky, "THz spectroscopy and source characterization by optoelectronic interferometry," *Applied Physics Letters*, vol. 60, pp. 1070-1072, 1992.

[11] C. Karadi, S. Jauhar, L. P. Kouwenhoven, K. Wald, J. Orenstein, and P. L. McEuen, "Dyamic response of a quantum point contact," *Journal of the Optical Society of America B*, vol. 11, pp. 2566-2571, 1994.

[12] Y. Konishi, M. Kamegawa, M. Case, Y. Ruai, S. T. Allen, and M. J. W. Rodwell, "A broadband free-space millimeter-wave vector transmission measurement system," *IEEE Transactions on Microwave Theory and Techniques*, vol. 42, pp. 1131-9, 1994.

[13] J. S. Bostak, "All-electronic generation and detection of terahertz free-space radiation with applications to free-space terahertz spectroscopy," Ph. D. Thesis, Stanford University, 1994.