The Effects of Beamsplitter Emission in a Balanced Fourier Transform Spectrometer

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***Abstract*—A Fourier transform spectrometer (FTS), with its high throughput and free spectral range, represents the most efficient class of spectrometer and is ideally suited to applications in the energy starved THz region. For broad-band/continuum observations, the challenging dynamic range requirements of the interferogram signal near zero optical path difference can be reduced by port balancing, a technique in which a broadband spectral source is placed at the second, complementary FTS input port. Studies of the performance of the Herschel SPIRE FTS instrument have shown that beamsplitter emission may contribute significantly to the measured interferogram when port balancing is optimum[1]. In this paper we describe an experiment that has been designed to explore this effect further, and compare the results with a theoretical model.**

I. Introduction and Background

The SPIRE instrument on-board the Herschel Space Observatory contains an imaging Fourier transform spectrometer (FTS) of the Mach-Zehnder configuration, which uses a calibration source (SCAL) at its second input port (port B) in order to compensate for the blackbody emission of the passively cooled telescope observed through the primary input port (port A). Port balancing is particularly advantageous in cases where blackbody emission from the input optics of an instrument produce a radiative background which dominates a much weaker source signal, a case frequently found in far-infrared and submillimetre astronomy. During performance testing of the SPIRE FTS it was found that beamsplitter emission resulted in a significant modulated signal while the input ports were balanced[1]. This work describes an in-depth study of the effects of beamsplitter emission in FTS spectra.

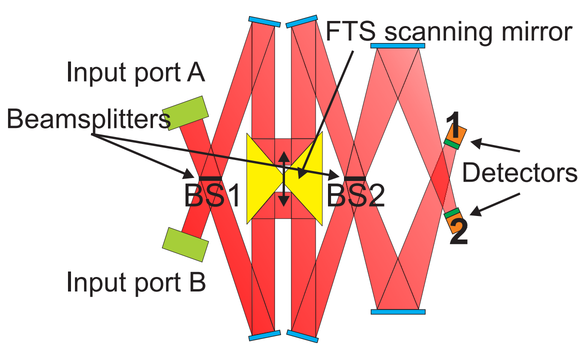

Fig. 1. Diagram of the SPIRE Fourier transform spectrometer.

The SPIRE FTS (see Figure 1) contains two identical beamsplitters (BS1 and BS2); each of which is characterized by a reflection coefficient, $re^{i\rho}$, and a transmission coefficient, $te^{i\tau}$. The reflectance and transmittance are given by $R = re^{i\rho}re^{-i\rho} = r^2$ and $T = t^2$ respectively, and the phase difference between reflection and transmission is given by $\phi = \rho - \tau$, which is ideally $\pi/2$. Although radiative emission from both beamsplitters contributes to the total flux received at either output, only the emission from the first beamsplitter may contribute to the modulated interferogram signal[2]. For spectra $E_A(\sigma)$ in input port A, $E_B(\sigma)$ in input port B, and $E_{\rm BS1}(\sigma)$ from BS1, the modulated interferogram observed at either output port 1 or 2 can be expressed as:

$$\begin{aligned} I_{\frac{1}{2}}(z) \quad = \quad & \int 2RTE^2_{\frac{A}{B}}(\sigma)\cos(2\pi\sigma z)d\sigma \\ & + \int 2RTE^2_{\frac{B}{A}}(\sigma)\cos(2\pi\sigma z \mp 2\phi)d\sigma \qquad (1) \\ & + \int 2\sqrt{RT}E^2_{BS1}(\sigma)\cos(2\pi\sigma z \mp \phi)d\sigma. \end{aligned}$$

For a well balanced interferometer (i.e. $E_A \approx E_B$), the E_B integral complements the E_A integral, because of the 2ϕ term (ideally π). In this situation the E_{BS1} term may dominate the observed signal.

II. Experimental Design

An independent study using an FTS of design similar to that of SPIRE was performed in order to quantify the effects of beamsplitter self-emission in a balanced FTS. Although SPIRE is tested under vacuum at cryogenic temperatures, similar effects were observed with a Mach-Zehnder FTS at room temperature under atmospheric pressure. In this study two identical, independently controlled, blackbody sources were constructed to be used at both FTS input ports (A & B, Figure 1). A mechanism to heat the beamsplitter above ambient temperature was also devised. The experiments performed may be classified under two categories. The first class of experiment involves the recording of highly-oversampled low-resolution interferograms while one input is held at a constant temperature, T$_c$, while the other is cooled from a temperature greater than to a temperature less than the other source (typically spanning a range of T$_c \pm 3\ K$). The second class of experiments involves heating the beamsplitter above ambient temperature and allowing it to cool with both input sources maintained at the same temperature, again while recording

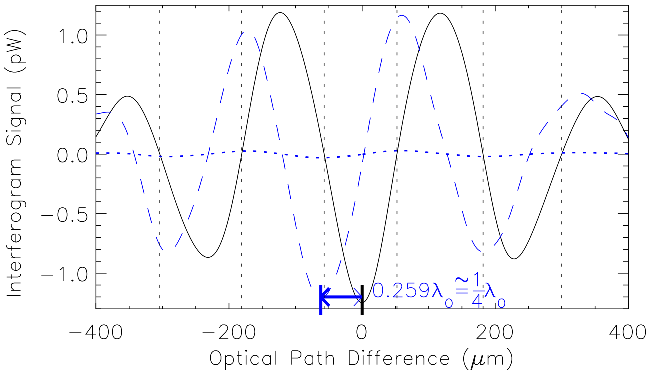

Fig. 2. Recorded interferograms illustrating unbalanced (solid) and balanced (dashed) characteristics. Also shown is the balanced signal with amplitude scaled to that of the unbalanced interferogram (long dashes). Zero crossings of the unbalanced interferogram are shown to highlight the phase difference between the two signals.

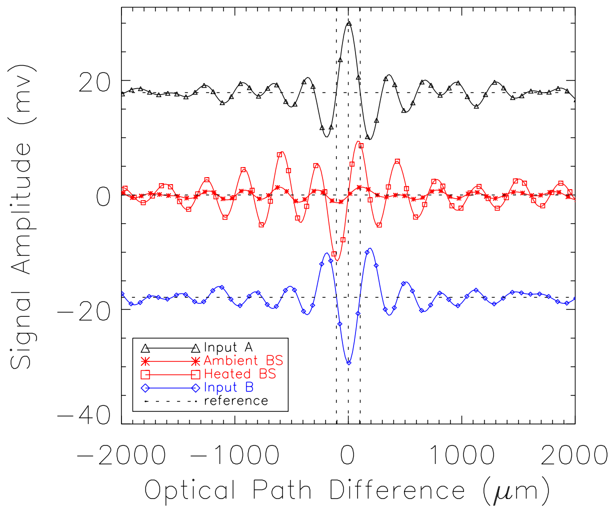

Fig. 3. Wide-band ($\sim$ $300 - 1100$ μm) interferograms illustrating unbalanced (triangles and diamonds), balanced (asterisks), and balanced with enhanced beamsplitter emission (squares) instrumental characteristics (offset for clarity).

highly-oversampled low-resolution interferograms. These experiments are performed in the far-infrared with several narrow and wide band filters employed to characterize this effect at a variety of frequencies and bandwidths. The first set of experiments is designed to determine the point of optimal port balancing and demonstrate the range of temperature over which beamsplitter self-emission in a balanced FTS is significant. The second class of experiments proves that the source of the asymmetric component of the port-balanced interferogram is in fact the beamsplitter self-emission.

III. Results

An interferogram dominated by beamsplitter emission will show a phase shift in the apparent location of ZPD in both output ports corresponding to the ϕ term in Equation 1. Figure 2 demonstrates this for the SPIRE spectrometer where a shift in the apparent position of ZPD of $\sim \lambda_o/4$ is observed, indicating a phase shift of $\sim \pi/2$ between input port and beamsplitter emission dominant interferograms.

According to Equation 1, only the emission from the *first*

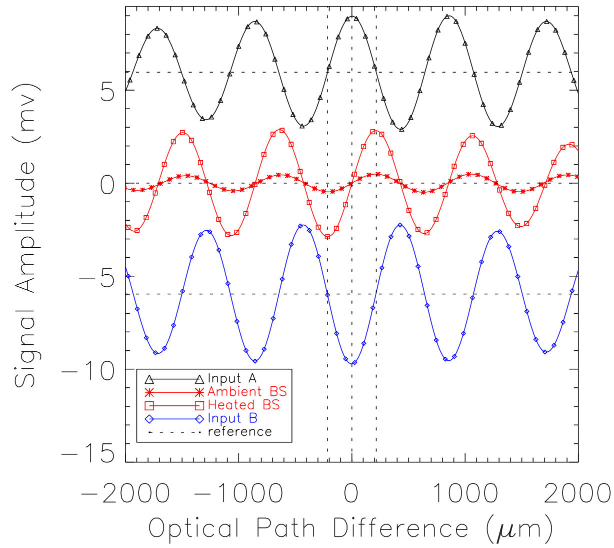

Fig. 4. Beamsplitter self-emission observed in narrow-band ($\sim$ 850 μm) interferograms. Identification of unbalanced and balanced scans is the same as that of Figure 3.

beamsplitter contributes to the *modulated* optical signal, i.e. the interferogram[2]. In addition to balancing precisely both input sources, the first beamsplitter was heated above ambient temperature during port compensation scans to enhance the self-emission effect. Figures 3 & 4 show observed interferograms with enhanced beamsplitter emission for wide and narrow optical bands respectively, and also include port A & B dominant scans for reference.

Beamsplitter emission must be accounted for in situations where signal amplitude due to beamsplitter emission is greater than the noise floor of the interferogram. It is observed that the beamsplitter emission maintains its $\sim \pi/2$ phase while increasing in amplitude while the beamsplitter is heated, although a beampslitter would not be intentionally heated in practice. Subtraction of a well balanced interferogram (i.e. the beamsplitter dominant case) from relevant interferograms is seen to re-symmetrize the interferogram about ZPD and reduce the associated spectral artefacts.

IV. Conclusions

Results from a detailed study of the effect of beamsplitter self-emission on port-balanced FTS interferograms have been discussed. This effect has been observed within FTS instruments in a variety of environments (i.e. atmospheric pressure and room temperature down to vacuum and cryogenic temperatures), with the effect enhanced by externally heating the first beamsplitter. Beamsplitter emission may be removed empirically with calibration data. Further results of this study are in preparation.

References

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