Far Infrared Interferometer Technology Development A Progress Report

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1 Introduction

We report on the progress of developing cryogenic delay lines and integrated optics components for far-infrared direct-detection interferometry at wavelengths from 40 to 300 μm. To achieve background-limited performance at these wavelengths, the interferometer optics and delay lines must be cooled to near liquid Helium temperatures. Our cryogenic delay line designs incorporate a number of novel features to meet the interferometer requirements under these conditions. The integrated optics effort has focused on producing single-mode spatial filters and beam combiners for operation at the same wavelengths using laser micro-machined waveguide structures.

2 Cryogenic Delay Lines

An ideal delay line should provide smooth, predictable, controllable motion in one degree of freedom while remaining rigid in the other five degrees of freedom. Because of our concerns about the ability of bearings to operate very smoothly at cryogenic temperatures for long periods of time, we have concentrated on delay line designs that do not use axles. For the far infrared, we anticipate delay line operation at temperatures as low as 4 Kelvin. The two basic concepts we are exploring to make a scanning stage are a "strapped-wheel" design and a "flex-blade" design.

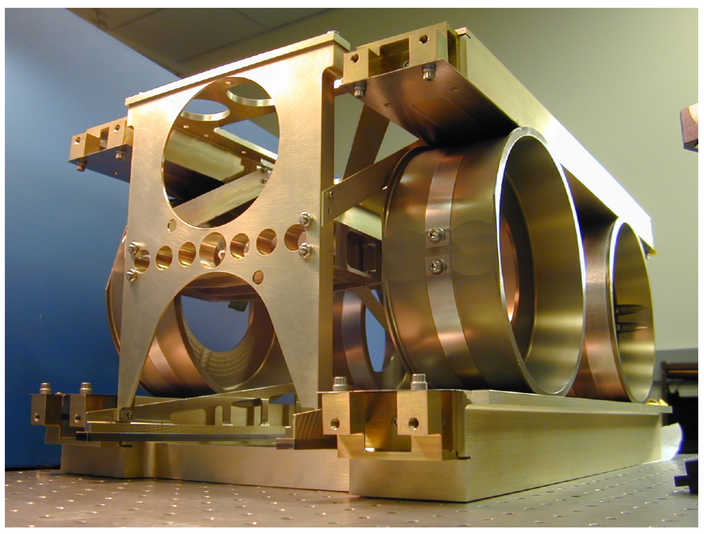

Figure 1: The strapped-wheel delay line. The optics are suspended from the upper stage. Alignment of the scanning stage is controlled by adjusting the wheel strap preload on individual wheels. This delay line has 25 cm of physical travel.

The strapped-wheel delay line, shown in Fig. 1, provides linear motion of an optical stage by rolling a platform on wheels with respect to a fixed stage. The wheels are strapped to the stages to guide the wheel path. The straps are tensioned with a flexure-based preload. One each side, the wheels are strapped together to react the preload force in wheel-to-wheel strap tension. The upper and lower stages are held together with a magnetic preload. The magnets, held in counter bores in the fixed stage, pull on steel bars that are held in close proximity, suspended from the optics stage. The optics stage is translated using a stepper motor working against a spring preload. The alignment consists of adjusting the individual wheel strap preloads to minimize the lateral run-out of the optical stage.

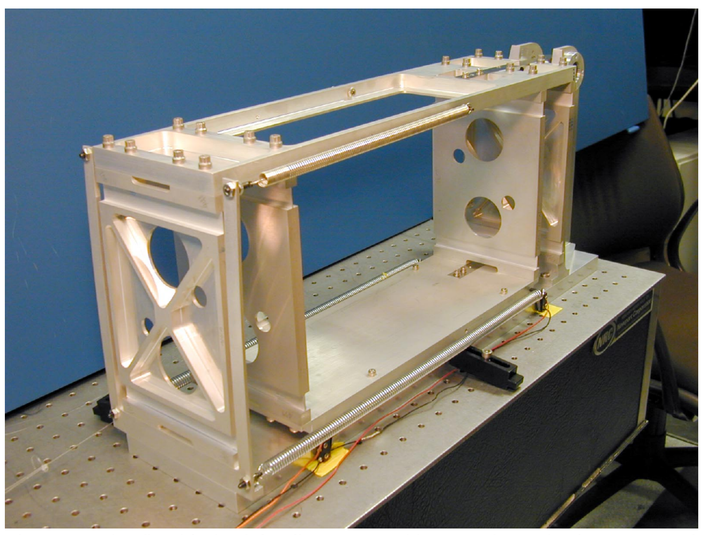

Figure 2: The flex-blade delay line stage without optics. The lower stage is driven at twice the rate of the upper stage so that there is no net vertical shear with respect to the input beam.

The flex-blade delay line, shown in Fig. 2, is based on a nested pair of parallel-motion flexures arranged so that the inner stage cancels the shear caused by the outer stage during translation. The inner and outer stages must be synchronized so that the inner stage translates twice as far as the outer stage. Our design uses a single stepper motor driving the inner and outer stages via a stepped pulley and two drive tapes, shown in Fig. 3. The pulley diameter is sized to move the inner stage twice the distance of the outer stage. A flexure-based preload adjustment for the drive tape of the outer stage can be adjusted to phase the inner and outer stage motion. The stepper motor works against a preload applied to the inner and outer stages through a symmetric spring system.

We have completed warm tests on our prototype delay lines to characterize their run-out and tilt as a function of position in their range of motion. For these tests we used capacitance sensors (in both averaged and differential mode) to measure displacement and tilt of the stages and used an autocollimator to measure the tilt of a fiducial optic on the delay line. For the first-generation strapped-wheel design, we performed a preliminary cryogenic test at 117 Kelvin, and several long-duration tests.

Warm run-out tests for the first generation strapped-wheel delay line indicated straightness of travel at the ∼15 μm level for most of the range of motion. Recent tests of the flex-blade delay line, plotted in Fig. 4, have demonstrated tilt errors at the ±2 arcsecond level.

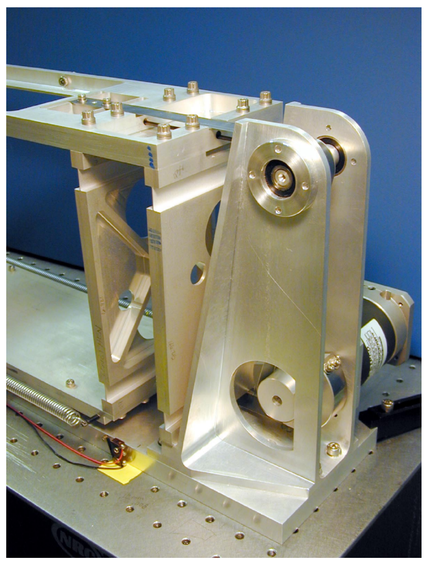

Figure 3: Detail of the flexure assembly in the flex-blade delay line design. Note the flexure preload termination of the drive strap for the upper stage. Adjustment of this preload synchronizes the motion of the inner and outer stages.

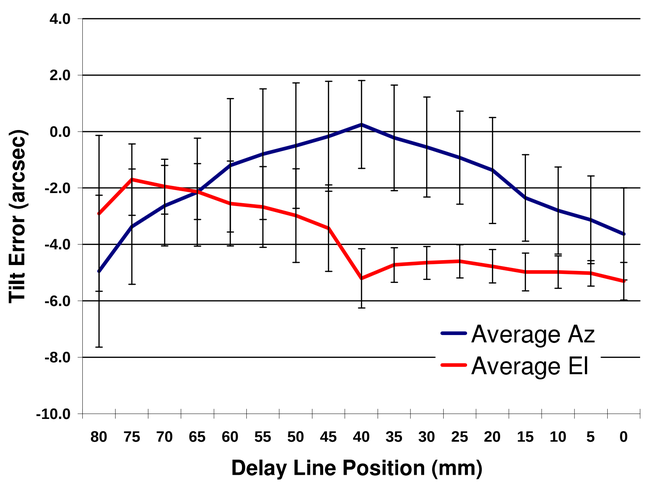

Figure 4: Performance curves for the flex-blade delay line shown in Figs. 2 and 3. Tilt errors are shown as a function of delay-line position, indicating a straightness of travel of ±2 arcseconds in both azimuth and elevation.

We are presently investigating a cat's eye optical design for the delay lines. The small secondary mirror of the cat's eye is a natural location for fast, small-amplitude optical, path length control using a piezo-electric transducer (PZT). PZT actuators have high bandwidth (∼1 kHz) but limited range of motion. This range of motion decreases to ∼25% of the warm value at 4 Kelvin. To compensate for the reduction in PZT range of motion at low temperature, we have developed a momentum compensated, mechanical amplifier. This device, shown in Fig. 5, is based on a pair of 4-bar linkages symmetrically driven by the PZT. The angle between the 4-bar linkage segments and the load axis of the PZT determines the theoretical mechanical advantage. With the system we have designed, we expect to recover most of the PZT range of motion.

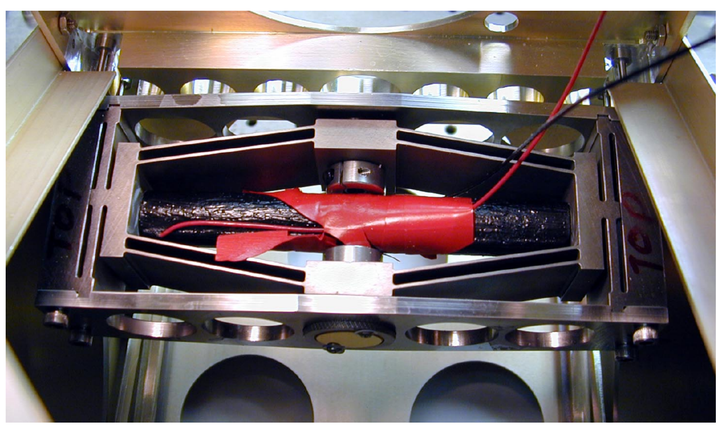

Figure 5: A top view of the momentum compensated, 4:1, mechanical amplifier. This device is intended to compensate for loss in PZT stroke at cryogenic temperatures. In this configuration, the PZT modulates optical path-difference by adjusting the position of the secondary in a cat's eye optical system.

We are presently procuring a large liquid nitrogen dewar for testing of the delay lines. Prior cold tests have proven the designs to be sound. The dewar will provide a thermally and mechanically stable environment for measurement and delay line characterization. Characterization of the mechanical properties of both delay line designs as well as the dynamic range and accuracy of the control system design will be tested at 77 K°.

3 Integrated Optics

Our interest in integrated optics for cryogenic space-based interferometers is based on simplifying the instrument alignment process (eliminating control points), making the alignment robust to thermal cycling, and reducing the instrument mass. Given the recent advances in laser micro-machining, it is straight-forward to implement some types of traditional free-space optics functions as conductive waveguide structures. The laser micro-machining process uses a laser to selectively remove material. The machining is performed on a silicon substrate and results in two "halves" of the waveguide structure. The two halves are then gold coated and mounted together to form the completed device. Because effects from residual surface texture increase as the wavelength decreases, it is easier to make a given structure for longer wavelength operation.

Our collaboration aims to exploit the micro-machining process under development at the University of Arizona for making spatial filters, power splitters, and beam combiners for far-infrared interferometry. Our eventual goal is to make multi-way infrared beam combiners for wavelengths from 10 to 400 μm.

Because of the large effective numerical aperture of the waveguide, horns are needed to couple radiation in and out of the waveguide structures. We have been making horns and circular waveguide sections for single-mode spatial filtering (Figs. 6 and 7). A pair of back-to-back feed horns joined by a section of single-mode waveguide designed to operate as a spatial filter at 60 μm will be tested for transmission and spatial mode rejection.

We have also modeled a variety of beam combiner designs for fabrication and testing in the near future. An example of a promising design is the "rat-race" power combiner shown in Fig. 8.

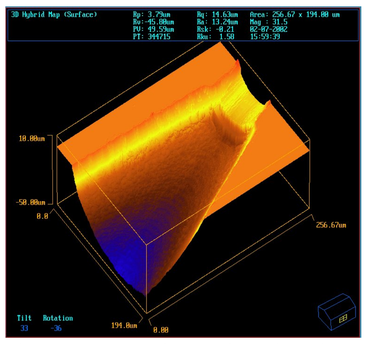

Figure 6: Scan of a section of a micro-machined feed horn.

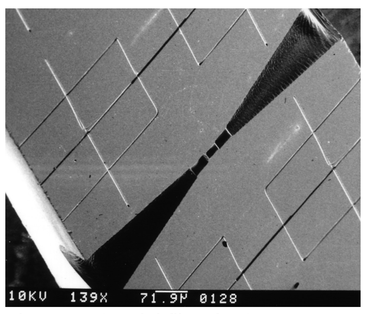

Figure 7: Spatial filter for $\lambda = 60$ μm. Cross section of a pair of back-to-back feedhorns joined with a section of single-mode waveguide.

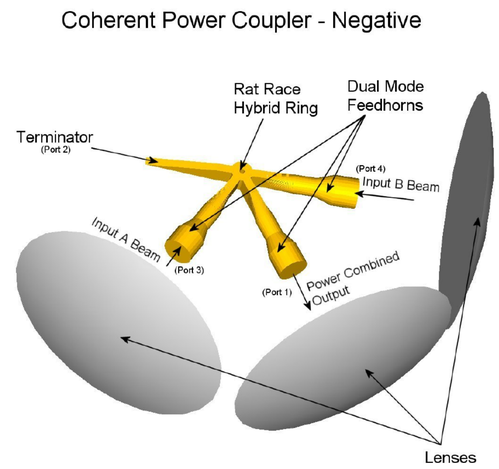

Figure 8: Beam combiner concept. The "rat-race" power combiner, with a lens and horn combination for coupling power into and out of the device.

4 Conclusion

We are rapidly assembling the constituent pieces, the building blocks, necessary to build and demonstrate a far-infrared, spatial interferometer testbed operating in the 10 to 300 μm range. Our cryogenic delay line concepts are operating warm and will be tested cold as soon as our test dewar is installed and commissioned. The integrated optics for far-infrared spatial interferometry development effort has great potential for simplifying interferometer optical systems. Performance tests of both technologies will take place within the next year.

See the related talk:

C.Y. Drouet d'Aubigny et al. "Laser micromachining of waveguide devices for sub-mm and far IR interferometry and detector arrays," Wednesday, 28 August 2002, 2:30 pm, Kings Ballroom 2.

References:
C.K. Walker *et al.* 1998, Proc. SPIE 3357. P.R. Lawson *et al.* 2000, Bull. Astron. Soc. Am. **32**, 1426; M.R. Swain *et al.* 2002, Proc. 36th Liège International Astrophys. Colloq.

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