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PROGRESS IN LABORATORY RESEARCH FOR FUNDAMENTAL PHYSICS SPACE MISSIONS USING OPTICAL DEVICES

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ABSTRACT

In this paper, we present the progress in our laboratory studies for fundamental physics space missions using optical devices. Specifically, we report on our progress in long fibre-linked heterodyne interferometry, tunable fibre directional coupler, fibre delay-line and picometer real-time motion control.

INTRODUCTION

Fundamental physics is emerging as one of the three important disciplines in space science missions. Compared to space missions in other two disciplines—solar system science and astronomy/astrophysics, fundamental physics missions have an even higher technological challenge. Technological challenge drives technological innovation. However, before these fundamental physics mission concepts become feasible, laboratory R & D's are required to solve the major challenges.

There are two general categories of these fundamental physics missions with high technological challenges: cryogenic and optical. LPE (Lambda Point Experiment), Gravity Probe B (Relativity Gyroscope Experiment) and STEP (Satellite Test of the Equivalence Principle) missions are cryogenic missions. LISA (Laser Interferometer Space Antenna) and ASTROD (Astrodynamical Space Test of Relativity using Optical Device) missions are optical missions. LISA (ESA, 1994) is a gravitational wave observatory mission concept. ASTROD (Ni, Sandford, *et al.*, 1996) is a multipurpose mission concept using drag-free spacecraft in solar orbits to combine high-precision measurement of relativistic effects, measurement of solar angular momentum via Lense-Thirring effect, better determination of the orbital elements of major asteroids, improvement in the measurement of G and the detection of low-frequency gravitational waves in a single mission. A simple two spacecraft implementation is to have each spacecraft in separate solar orbit carry a payload of a proof mass, two telescopes two lasers, a clock, and a drag-free system (Ni, Wu and Shy, 1996). In the following, we present the progress in our laboratory studies for heterodyne interferometry, picometer real-time motion control, tunable fibre directional coupler and fibre delay-line.

FIBRE-LINKED HETERODYNE INTERFEROMETRY

Single-mode optical fibers play very important roles in delivering light and in interferometry. They have important applications in the optical communication systems and in space missions (Ni, Shy *et al.*, 1996). However, the optical phase in a transmitting fiber is very sensitive to the environmental perturbations, such as temperature and vibration perturbations. For applications requiring the transmission of low-phase-noise signals, induced phase noise cancellation is crucial. Recently Ma *et al.* (1994) have measured the optical fiber induced phase noise and invented a simple and effective technique for accurate cancellation of the phase noise in travelling a 25 m jacketed fiber. Using this technique they were able to reduce the fiber's kHz-level of broadening to sub-mHz domain.

Our phase noise cancellation scheme (Shy *et al.*, 1996) is shown in Fig. 1. The 1319 nm Nd:YAG ring lasers and 26.27-km single-mode bare optical fibre are placed on an optical breadboard. A half wave

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plate HWP was placed in front of laser 1 to optimize the beatnote signal detected by photodiode D1 which was used to phase lock laser 1 to laser 2 at an offset frequency 0.2-2.5 GHz synthesized by the signal generator SG1. The heterodyne beatnote linewidth after gone through 26.27 km fibre is analyzed by a fast Fourier transform ananlyzer FFT and it is less than 1 mHz. For the 0.2 GHz offset locking, the fringe resolution is better than 1/100. This ability of nearly perfect cancellation of the fiber induced phase fluctuation makes the study of the second-order relativistic light deflection of the Sun using long-baseline fibre-linked interferometers possible. It also enables us to do high precision astrodynamical angle and range measurements. In addition, we can distribute the standard RF frequency to distant locations using optical fibers. We may find applications in the intercomparison of atomic clocks located at different laboratories, with accuracy comparable to that of space synchronization scheme. This delivery scheme also demonstrate itself as a successful technique for sub-milli-Hertz relative optical frequency stabilization for subcarrier multiplexing fibre communications (Tsao et al., 1996).

FIBRE COUPLER AND FIBRE DELAY LINE

Tunable fibre directional couplers with high tuning speed are important for switching optical paths in optical space missions. Having adopted silicon wafers as polishing substrates, we have made fibre coupler-halves with a long effective interaction length and negligible loss (Ma and Tseng, 1995). Using micro-electronic techniques, we etch several V-grooves having radius of curvature R from 8 to 12 m in a (100)-oriented silicon wafer. Unjacketed 830-nm single-mode fiber sections are separately embedded into etched grooves of a wafer and polished simultaneously. The proximity of polished coupler-halves to fiber core is kept within 1.0 μm. Wafers composing polished fibers are cut and the width of each polished coupler-half is about 5 mm. We use a tunable Ti-sapphire laser as the light source in our measurements. Fibers so polished are sensitive in liquid-drop measurements and show negligible loss. Two coupler-halves are chosen and the back surface of each polished sample is fixed on a flat plate. These two coupler-halves are put together as shown in on the top of Fig. 2 and index-matching oil is sandwiched between their polished surfaces. To facilitate our alignment, one of the assembled coupler-half is mounted on an X-Y stage. Because of a long effective length, we can couple light from one coupler-half to another without difficulty. The mechanical tunability of these couplers is close to 100%. They can also be used as multi/demultiplexers. The lower part of figure 2 shows typical normalized powers of two output ports of a coupler (Hsu et al., 1996). According to this figure, the corresponding $\Delta\lambda$ is 100 nm. By adjusting the movable coupler-half along the longitudinal direction, similar results as shown in Fig. 2 are seen except that the curves are shifted.

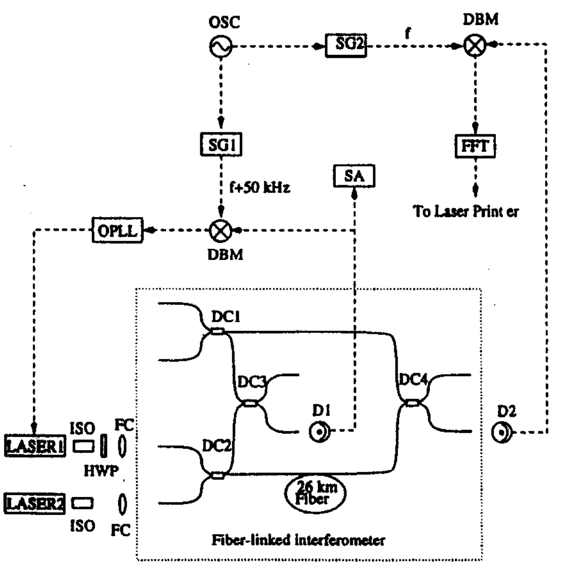

Fig. 1 The fiber-linked interferometer and the experimnetal setup. Here SA is Spectrum analyzer, DBM is double balanced mixer, FC is fiber coupler, and ISO is Faraday optical isolator. See the text for rest.

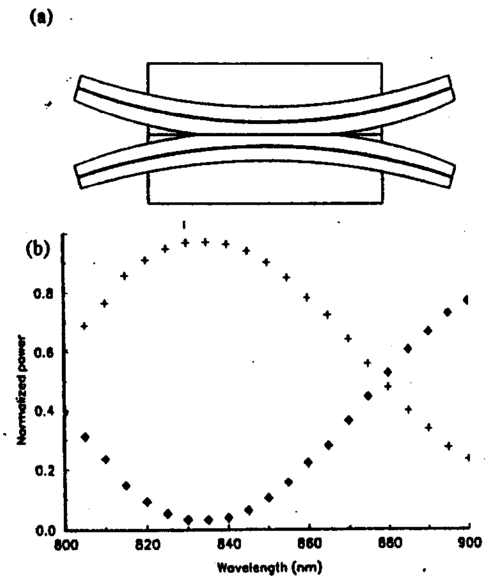

Fig. 2(a) Schematic of a fibre coupler made of two coupler halves; 2(b) The measured normalized powers of two output ports of a tunable fiber coupler as a function of wavelength. Symbols black diamond and plus represent the uncoupled and coupled ports, respectively.

When a large lateral offset is purposely made by us, a larger $\Delta\lambda$ is found. Thus, we demonstrate polished fiber couplers as multi/demultiplexers. Further development of these components will be useful in space communications.

For space-borne astronomical interferometers, all-optical fibre delay lines are desirable and necessary to minimize the cost. A schematic configuration for fibre delay lines is shown in Fig. 3 (Ni, Pan, *et al.*, 1996). This same configuration can also be used for earth-bound astronomical interferometers. To meet the tuning speed requirement of the delay line, we will apply voltage to change the index matching liquid crystal between two coupler-halves. Response time of 1 ms are expected. This time scale is much shorter than the characteristic atmospheric fluctuation time scale and would be adequate for delay line to be used in ground-based interferometers. We will study the characteristics of the delay lines made of the mechanically tunable directional couplers and, then, those made of the electrically tunable directional couplers. After that, we will make a prototype of all-optical fibre delay line with continuonsly (1 ms) variable delay and study its characteristics.

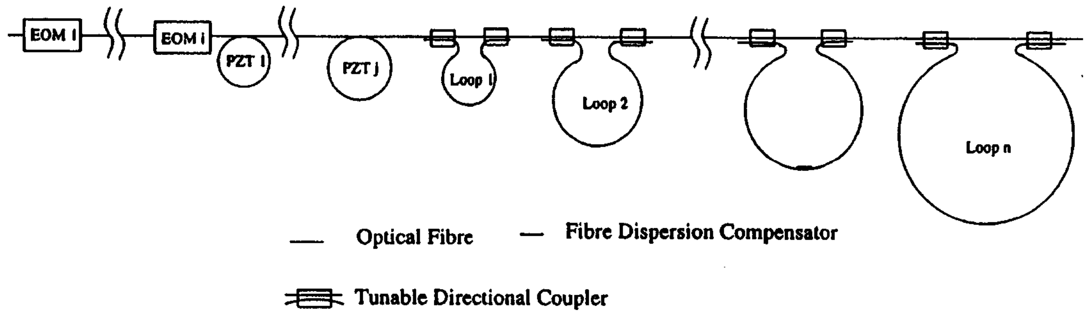

Fig. 3. A schematic configuration of fibre delay lines

PICOMETER REAL-TIME MOTION CONTROL

In the drag-free control of spacecraft, we need precision metrology sensor to sense the position of the spacecraft relative to the proof mass. For this purpose, there are two choices — capacitance sensor and laser metrology sensor. For a laser metrology sensor system, larger gap is possible. Hence, less local gravitational disturbances are incurred and better accuracy in controlling the deviation from the geodesics can be achieved. Recently we have proposed to use laser metrology and optical methods for performing an equivalence principle test in space (Ni, 1996). All these need picometer real-time laser metrology and real-time motion control. For ultra-high precision interferometric measurement, the optical path length in optical device need to be measured and controlled very accurately also.

For laser metrology, we use mid-point cyclic average to minimize nonlinearity error (Yeh *et al., 1995*). After fourth cyclic average, the residual nonlinearity error is about 1.5 pm rms. For real-time control, we need real-time measurement. We use PZT's to modulate a small mirror to perform real-time averaging. We used two other sets of PZT's for motion and motion correction, and reached real-time measuring error of 560 pm and real-time control error of 700 pm rms. This real-time control was for a 440 nm run (Yeh *et al., 1995*). To reach a longer span, we use the experimental setup shown in Fig. 4 for study. For data acquisition, data processing and control, we use a VME-bus Heurikon single board computer (Nitro60 with Motorola 68060 CPU) with VxWorks. We use a PI PZT to drive the flexure stage. The laser metrology mirror is mounted on three PZT's for position measurement. This mirror can be modulated by PZT's for mid-point cyclic average to minimize nonlinearity error in real-time. The PI PZT has a length-change range of 12.6 μm for 100 V. The nonlinearity and hysteresis of this PZT is measured and compiled as a look-up table using the laser interferometer system before real-time motion control is to be implemented. For real-time motion control, the D/A voltage to be applied is first calculated using the look-up table. After the initiation, the error signal for the prescribed motion is fed back to the PI PZT as an increment voltage through D/A. The real-time motion control errors for 10 μm linear and quadratic motions are about 900 pm rms as shown on top of Fig.5. These errors are dominately quantization errors

due to 12 bit DAC. The rms error after 16-point average is 0.21 nm as shown in the lower part of Fig.5. For longer motions and/or better precisions, more stages will be implemented.

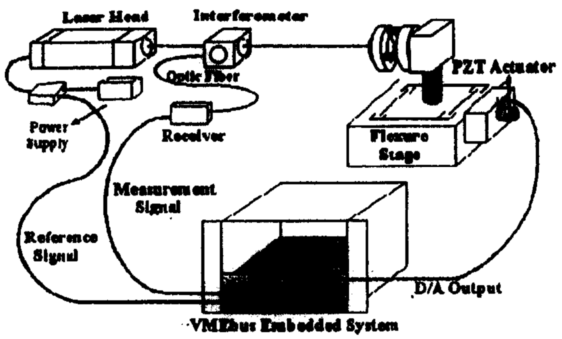

Figure 4. Experimental setup for picometer real-time motion control

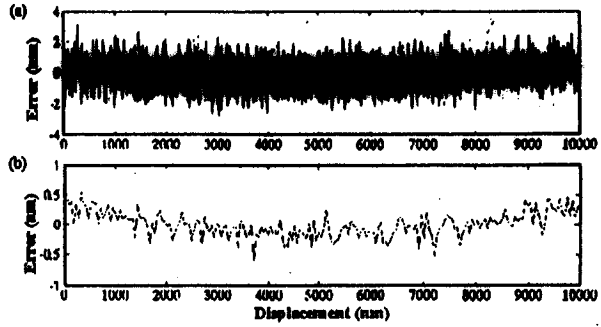

Figure 5. (a) The errors of real-time motion control for linear motion.
(b) After sixteen point average, the residue becomes 0.21 nm.

OUTLOOK

High precision optical missions enable us to study fundamental problems in physics and astrophysics. These missions present high-technology challenges which demand matching R & D's. These R & D's will benefit optical space communications and find important earth-bound applications.

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