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Principle demonstration of fine pointing control system for inter-satellite laser communication

DONG YuHui[1,2†], LIU HeShan[1,2†], LUO ZiRen[1], LI YuQiong[1] & JIN Gang[1*]

[1] *National Microgravity Laboratory (NML), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China;*
[2] *University of Chinese Academy of Sciences, Beijing 100190, China*

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Due to high data rates and reliability, inter-satellite laser communication has developed rapidly in these days. However, the stability of the laser beam pointing is still a key technique which needs to be solved; otherwise, the beam pointing jitter noise would reduce the communication quality or, even worse, would make the inter-satellite laser communication impossible. For this purpose, a bench-top of the fine beam pointing control system has been built and tested for inter-satellite laser communication. The pointing offset of more than 100 μrad is produced by the steering mirror. With beam pointing control system turned on, the offset could be rapidly suppressed to lower than 100 nrad in less than 0.5 s. Moreover, the pointing stability can be kept at 40 nrad for yaw motion and 62 nrad for pitch motion, when the received beam jitter is set at 20 μrad.

laser beam pointing control, inter-satellite laser communication, heterodyne laser interferometer, differential wave-front sensing (DWS) technique

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1 Introduction

Laser communication is thought to be the most promising future inter-satellite communication strategy because of its high transmitting speed and reliability [1–5]. During the operation of the inter-satellite laser communication system, how to maintain the precision and stability of the laser pointing direction is a critical problem that needs to be solved [3–8]. Being maximally suppressed by the disturbance reduction system, the residual satellite vibration, which originates from a variety of sources, such as solar radiation, residual magnetic field, static gravity imbalance and structural interactions, is still coupled into the detected laser beam. The heterodyne contrast and the received power which is decreased by the pointing jitter will seriously influence the communication quality. Therefore, the beam pointing control system between two distant satellites has become a major issue for those missions and should be suppressed to sub-micro-radian regime [9–13].

A fine laser pointing control system based on differential wave-front sensing (DWS) [14–17] is introduced in this paper which could be integrated with the inter-satellite laser communication system (see Figure 1). The pointing jitter can be well suppressed by a pair of beam pointing control systems in two satellites, which can guarantee the communication quality in the inter-satellite communication. This pointing control system is inherited from space-borne laser interferometer gravitational wave (G.W.) detection missions [18–22]. To explore the most attractive G.W.s, the space-borne G.W. antennas are designed to measure pico-meter displacement in a distance of 10^5 to 10^7 km [23–27]. Beam

*Corresponding author (email: gajin@imech.ac.cn)
†Contributed equally to this work.

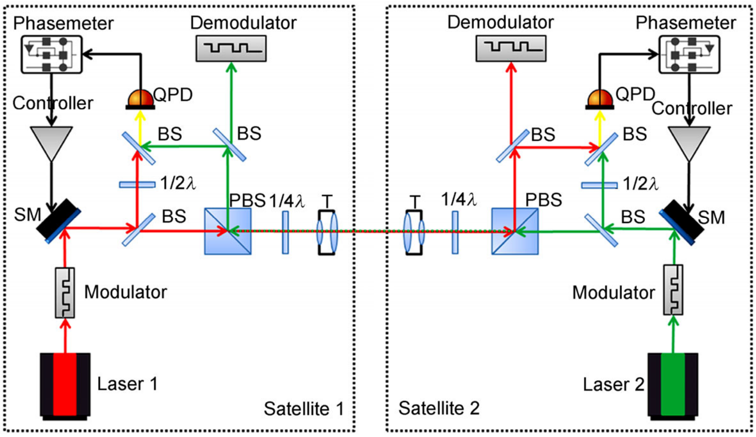

Figure 1 (Color online) Diagram of inter-satellite laser communication and its beam pointing system. BS: Beam splitter, PBS: Polarizing beam splitter, QPD: Quadrant photo detector, SM: Steering mirror and T: Telescope. Laser 1 shown in red transmits to satellite 2. Reflected by the PBS, part of laser 1 is demodulated by demodulating optical bench while the other part is heterodyne interfered with laser 2 shown in green. The DWS signal is produced by QPD and phasemeter and then sent to the beam pointing controller. The controller then commands the local steering mirror to adjust the local beam parallel to the receiving beam. It is the same case for laser 2 transmitting to satellite 1.

pointing noise is one of the most prominent noises in long baseline space laser interferometer and mainly dominated by laser pointing jitter. Thus, the G.W. antennas require extremely high accuracy and stability for the laser beam pointing direction control [28,29]. Taking the evolved Laser Interferometer Space Antenna (eLISA) as an example, the laser pointing jitter should be suppressed to 10 nrad in a long period of 10^2 to 10^3 s [30].

In this paper, a bench-top fine beam pointing control system is built and tested for inter-satellite laser communication based on the DWS technique. Under a closed loop, a static pointing offset larger than 100 μrad can be rapidly suppressed to 100 nrad within 0.5 s. Furthermore, we simulate a pointing jitter of 20 μrad in the laser pointing direction. After turning on the feedback pointing control system, the root mean square (RMS) of the pointing jitter for yaw and pitch motion has been reduced to 40 nrad and 62 nrad, respectively.

2 Experimental setups

To investigate the methodological laser beam pointing control system for inter-satellite laser communication, the heterodyne frequency generation part is essential shown in Figure 2(a). In this function part, a solid state laser at a wavelength of 1064 nm is used as the light source. After being divided by a beam splitter, the laser beams are frequency shifted by a pair of acoustic-optical modulators (AOMs), and the first-order Bragg diffracted beams with the maximum power are selected by the apertures. Then a pair of beams with stabilized heterodyne frequencies are generated and sent into the ultra-stable optical bench through fiber injected system as shown in Figure 2(b). The laser in red line used to simulate the transmitting laser is reflected by a steering mirror operated by the simulator; while the beam in green line represents the local laser. The two beams are superimposed and the relative angle is read out by the DWS angle-sensitive-system consisting of a quadrant photo detector (QPD) [31,32] and a phasemeter (PM) (Figure 3). DWS is a well-known technique with high sensitivity. In small range, the DWS phase signals $\Delta\theta$ between opposing halves of QPD can be approximated as [17]

$$\Delta\theta \approx \frac{16r}{3\lambda}\cdot\alpha = k\cdot\alpha, \tag{1}$$

where α is the relative wave-front tilt, r is the beam radius, λ is the laser wavelength and k is the conversion factor.

3 Calibration and experiments

Predicted by the DWS technique, the conversion factor k from geometrical angle to electrical phase difference should be initially calibrated by the experiment. Two degrees of freedom are required to depict the pointing jitter of the received light, where yaw motion indicates the horizontal misalignment and pitch motion presents the vertical fluctuation. In the experiment, the two degrees of freedom are calibrated independently. The steering mirror driven by a piezoelectric transducer (PZT) is steered from –300 μrad to 300 μrad in the yaw (pitch) motion, when the pitch (yaw) motion is kept at zero. The laser beam pointing data read out by the DWS technique is shown in Figure 4.

As shown in Figure 4, the solid lines are the linear regression lines of the DWS pointing error. The correlation coefficients of the linear fittings for yaw and pitch motions are 0.99995 and 0.99996, respectively, which indicates a good linearity between the DWS signal and relative angles in the working range from –300 μrad to 300 μrad. The con-

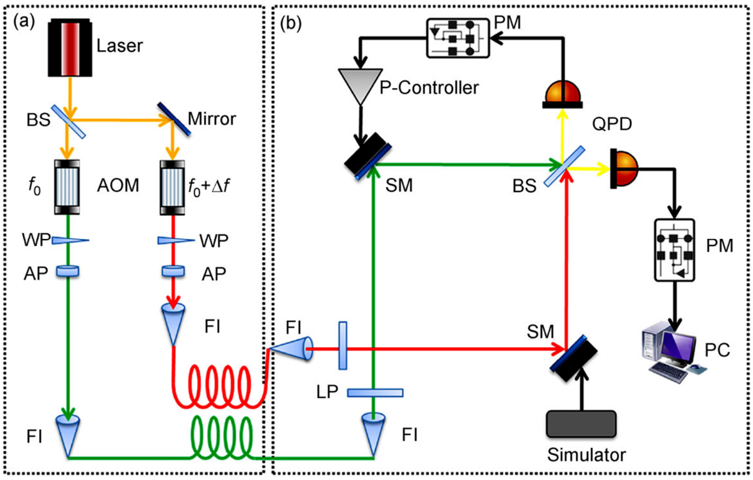

Figure 2 (Color online) Schematic diagram of the beam pointing control system. AOM: Acoustic-optical modulator, AP: Aperture, BS: 50:50 beam splitter, FI: Fiber injector, LP: Linear polarizer, P-Controller: Pointing controller, PM: Phasemeter, QPD: Quadrant photo detector, SM: Steering mirror and WP: Wedged plate.

Figure 3 (Color online) Picture of the ultra-stable optical bench of the beam pointing system.

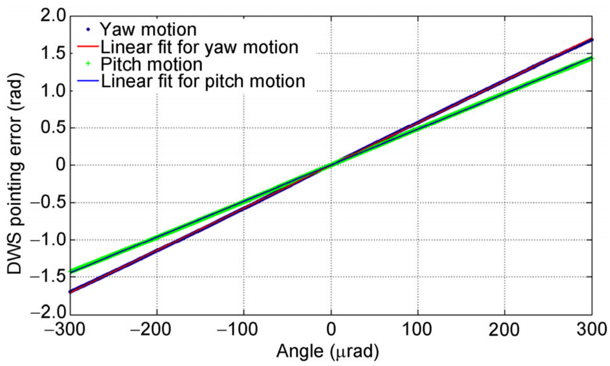

Figure 4 (Color online) Linear fit for yaw motion and pitch motion.

version factors for yaw and pitch motions obtained from linear fitting curve are 5689 rad/rad and 4815 rad/rad. The different amplitudes of the conversion factor may originate from various elements, such as imperfect overlapping of two interfering beams, inhomogeneous spatial distribution of the phase, or non-perpendicularity between the laser beams and photo-detector. In addition to high conversion factor, the DWS angle measurement can suppress common mode noises, which makes the high accuracy angle measurement and control possible.

3.1 Beam pointing control with a pointing offset of 100 μrad

In order to verify the dynamic response of the pointing system in large pointing offset, an offset angle of more than 100 μrad for yaw motion and pitch motion is simulated by the steering mirror. After 20 s free running, the closed loop of the pointing control system is turned on, and its performance is shown in Figure 5.

As shown in Figure 5, from 0 and 20 s, the pointing offsets are larger than 100 μrad in yaw motion and pitch motion. When the pointing control system is working at 20 s, the average angle offsets are rapidly decreased to lower than 100 nrad for yaw and pitch motions in less than 0.5 s.

3.2 Beam pointing control with a 20 μrad jitter

Pointing stability is a significant parameter which will seriously influence the bit error rate for inter-satellite laser communication. In this experiment, a laser beam of which the peak to peak pointing jitter is 20 μrad is driven by the steering mirror. After 5000 s free running, the pointing control system begins to work and the data detected by DWS system is shown in Figure 6.

As shown in Figure 6(a), under the closed loop of the pointing control, the RMS of the pointing jitter is suppressed from 7.1 μrad to less than 40 nrad in yaw motion. Meanwhile, the RMS of the pitch jitter is controlled from 7.0 μrad to 62 nrad, which is available in Figure 6(b). Moreover, the average of the pointing data is lower than

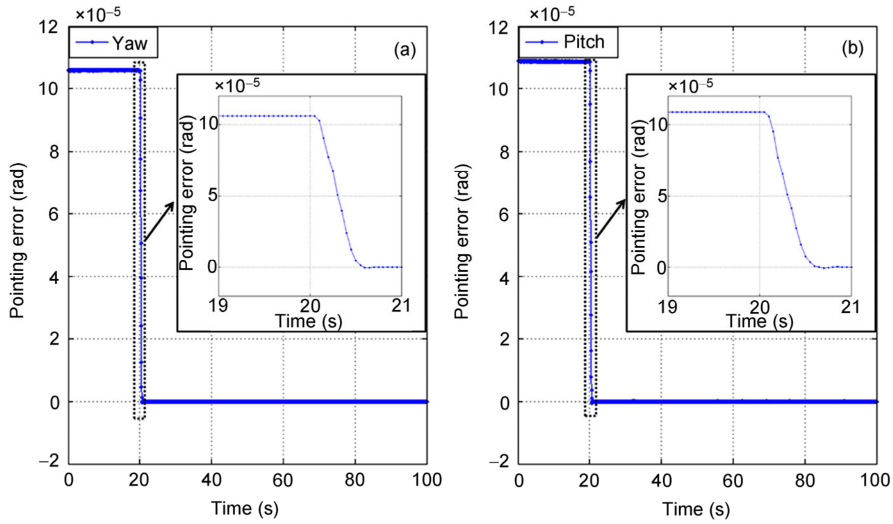

Figure 5 (Color online) Performance of beam pointing control with a pointing offset of 100 μrad for yaw and pitch motions.

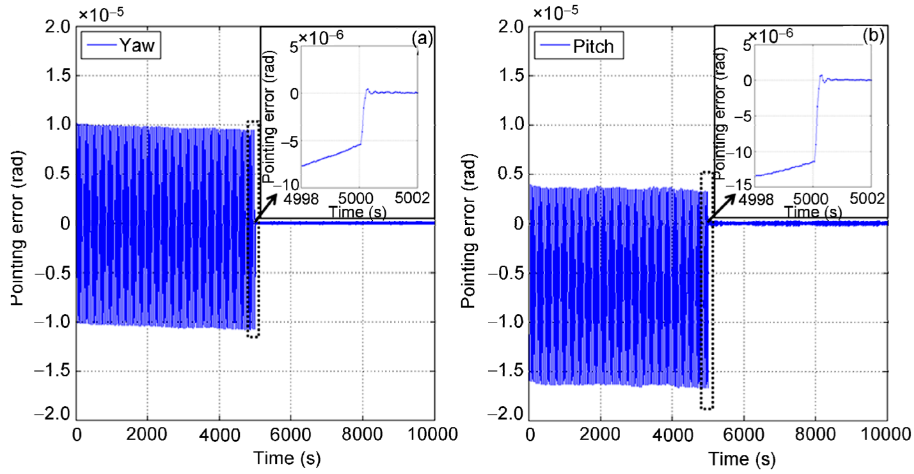

Figure 6 (Color online) Performance of the beam pointing control with a pointing jitter of which the peak to peak is 20 μrad for yaw and pitch motions.

100 nrad after the pointing control in yaw and pitch directions, respectively.

4 Conclusions

A bench-top of the feedback-based laser beam pointing system has been built and tested for inter-satellite laser communication. The DWS technique has been introduced to sense the relative wave-front tilt with high sensitivity and low noise. The offset pointing error of more than 100 μrad is produced by the steering mirror. With the beam pointing control system turned on, the offset has been rapidly suppressed to lower than 100 nrad for both yaw and pitch motions in less than 0.5 s, which indicates a good dynamic response. Moreover, the pointing stability can be kept at 40 nrad for yaw motion and 62 nrad for pitch motion, when the simulated received beam jitter is set at 20 μrad.

The environment of the inter-satellite laser communication is complicated and changeable. In the future, the simulated received beam jitter will be much closer to the real situation and the received laser power will be μW level. The following research will focus on the requirement of fine pointing control for inter-satellite laser communication in that situation.

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