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Novel satellite positioning system using Acousto-Optic Deflector

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ABSTRACT

Space gravitational wave detector in Japan named DECIGO is equilateral triangle-shaped laser interferometer with the arm length of 1000 km. For initial alignment and keeping formation of DECIGO, we propose novel satellite positioning system. Our system consists of a single-mode laser, acousto-optic deflectors (AOD) and a frequency counter. The diffraction beam from AOD deflects with the deflection angle which is proportional to the modulation frequency of AOD. The modulation frequency is swept to scan the angle of the deflected beam, and, at the remote end, a photo detector derives its position from the detected modulation frequency of the scanned deflected beam. Compared with the conventional optical method, our system is compact and has no moving elements, and the angle resolution of our system depends on not the optical diffraction limit but the resolution of frequency counting. In the current paper, we present the principle and the preliminary results of our system.

Keywords: satellite positioning, acousto-optic deflector, gravitational wave detector, frequency counting

1. INTRODUCTION

1.1 Gravitational wave detection

The motion of mass such as inspiral and merger of black hole binaries or explosion of super novae causes ripples in gravitational fields propagating with the speed of light, which is called gravitational wave (GW). Since GW has been predicted by Albert Einstein in 1916¹, many trials have been done to detect GW. As GW is temporal variation of spacetime quadrupole distortion, it can be detected by using a Michelson laser interferometer, and from 1990s, long-baseline laser interferometer gravitational wave detectors have been constructed in many countries such as LIGO, VIRGO, TAMA300, GEO600. However, it is very difficult to detect GW because the required strain sensitivity should be higher than $\delta l/l < 10^{-23}$. After a long straggle, Advanced LIGO group in US succeeded in the first direct detection of GW in 2015 which is generated from the inspiral and merger of black hole binaries with the mass of 36 $M_{\odot}$ and 29 $M_{\odot}$, called GW150914². The successive detections of GW are followed by GW150914, (GW170817 is generated from Neutron star binaries) and the Gravitational wave astronomy has just started. The gravitational wave detector which is a Fabry-Perot Michelson interferometer with the arm length of a few km constructed on the ground is called ground-based GW detector, and 3rd generation ground-based GW detectors such as Advanced LIGO³, Advanced VIRGO (France and Italy)⁴ and KAGRA (Japan)⁵ are now on going. The detection band of the ground-based GW detector is 10 Hz to 1 kHz, whose low frequency is limited by the seismic noise of the ground and its finite arm length. At lower frequency range, many attractive GW sources are expected such as inspiral and merger of heavier black hole binaries (intermediate-mass black hole: IMBH, super-massive black hole: SMBH with the mass of 10^5 - $10^{10} M_{\odot}$) or background GW from early universe. In order to access such GW at lower frequency band, the space gravitational wave detector is proposed, which can have much longer arm length in seismic noise free condition. Currently, two space gravitational wave detector projects are promoted, LISA in Europe and US⁶ and DECIGO in Japan⁷.

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1.2 DECIGO

DECIGO (DECi-hertz Gravitational-wave Observatory) is a Japanese space gravitational detector whose original idea has been proposed by Seto et.al.⁸. DECIGO consists of 3 satellites, forming a 1000-km triangle-shaped laser interferometer with Fabry-Perot cavities in each arm. Fig.1 shows the conceptual design of DECIGO and designed strain sensitivities. Compared with LISA, the detection band (0.1 to 10 Hz) is higher than that of LISA due from the shorter arm length (DECIGO-1,000 km, LISA-2,500,000 km), and the detection sensitivity is higher due from its configuration (DECIGO: Fabry-Perot Michelson interferometer, LISA: laser transponder). The scientific target of DECIGO is GW from IMBH and background black hole from early universe. Before launching DECIGO in 2030s, we also plans a milestone mission named B-DECIGO⁹ which has smaller size of DECIGO (shorter arm length of 100 km and smaller test masses) with almost the same configuration. In DECIGO/B-DECIGO, one of the key technologies is the formation flight of three spacecrafts (S/Cs). For initial alignment and keeping the formation of three S/Cs, the precision satellite positioning system is indispensable. In the current paper our novel position system based on frequency counting method is presented.

Figure 1. Conceptual design (left), designed strain sensitivity and targets (right) of Japanese space gravitational-wave detector DECIGO

2. SATELLITE POSITIONING SYSTEM

2.1 Principle

Precision satellite positioning is a key technology for formation flight or space optical communications. Satellite to satellite positioning used in inter-satellite optical communications (OISETS-ARTEMIS) is based on laser and imaging technologies¹⁰. In that system, one S/C (1st S/C) is broadly emitted laser beam, and in the other S/C (2nd S/C), the detected laser beam is imaged on the quadrature photo detector (QPD). The detection optical system is aligned so that the detected beam is focused on the center of QPD. The laser beam in 2nd S/C is emitted counter-propagated through the detection optics, and it reaches precisely to the 1st S/C and, in the consequences, the optical communication link is established. In our case, three S/Cs should be positioned with the each including angle of 60 degree. The master S/C makes two reference lines, and informs the other two S/Cs of their relative positions from each reference lines. In order to realize such a system, we use acousto-optic deflector (AOD). AOD is the Bragg diffraction components generated by the acoustic mode in the crystal. When the single longitudinal mode laser light with the frequency of f_L is introduced into the AOD which is driven at the modulation frequency of f_m , the input light is diffracted. The deflection angle θ between 0th and 1st order diffracted light is proportional to the modulation frequency of f_m

$$q = \frac{l \times f_m}{V_a} \quad (1)$$

where λ is the laser wavelength in the air, V_a is the acoustic velocity of the crystal. The frequency of the diffracted light is shifted at $\pm f_m$, where sign $\pm$ denotes the positive or negative diffraction. Therefore the deflection angle θ is derived

from the shifted frequency f_m of the diffracted light. The basic mechanism of our S/C positioning system is as follows. The master S/C propagates the 1st order diffracted light with the modulation frequency of f_m along the reference line. The deflected angle is scanned by sweeping the driving frequency of $f_m = f_0 + \Delta f$, which is used as signal beam with the frequency of $f_s = f_L + f_m$. Since the laser frequency, f_L , is too high to count by PD, the 0th order diffraction light is also propagated with the deflected light as the local oscillator. The slave S/C detects a part of frequency-scanned deflected light and 0th order light by a photo detector, whose frequencies are $f_L + f_m$ and f_L , respectively. The shifted frequency f_m is observed as the beat note frequency between signal and local beam. In the consequence, the slave S/Cs can get their relative position from the reference line (angle) by detecting the beat frequency of f_m , where the angle resolution of this system is free from the fluctuation of the laser frequency, f_L .

Figure 2. Schematic diagram of the positioning system, HWP: half wave plate, QWP: quarter wave plate, DDS: direct digital synthesizer, OSC: oscillator, VCA: voltage-controlled attenuator, PD: photo detector, BPF: band-pass filter

2.2 System set-up

We have developed the desktop model (DTM) of our satellite positioning system for the proof of principle. The schematic diagram of DTM is shown in Fig.2. A commercial Yb-doped fiber DFB laser (Koheras: BasicK Y10) with the wavelength of 1.03 μm is amplified by using a self-made Yb-doped fiber amplifier (YDFA), and 10 mW of second harmonics with the wavelength of 515 nm is generated by a periodically-poled Lithium Niobate crystal (PPLN), whose green light is used for the light source. The green light is introduced into an AOD (AOD1: Gooch&Housego R45100-5-6.5DEG) whose center frequency is 100 MHz and modulation band is ± 25 MHz (scanning frequency is 75 MHz to 125 MHz). A microwave frequency reference at 10 MHz is supplied to a self-made direct digital synthesizer (DDS) to generate the modulation signal, f_m , for driving AOD1 whose frequency can be controlled by a personal computer (PC). The modulation frequency at f_m is applied to AOD1 through a voltage-controlled attenuator (VCA) and a power amplifier to generate the 1st order diffraction light which is used as the signal beam (indicated by red arrows). The signal beam is collimated by using a convex lens (L1). At the remote end, the signal beam is detected by a photo detector (PD1: Hamamatsu S3883). The diameter of the PD1 is 1.5 mm which acts as the spatial filter, and the vertical axis of the propagated light is focused by using a cylindrical lens (CL1) placed in front of PD1 for increasing the detected power. In order to down-convert the detected signal from the optical to microwave region, the local oscillator should also illuminate PD1. As the position of the deflected signal beam is scanned to search the slave S/C, the local oscillator light, 0th order diffraction light, should be expanded to cover the scanning range of the signal beam, which decreases the detected power of local oscillator at PD1 and decreases the beat note signal. To solve this problem, a part of the green light is

picked off by using a polarized beam splitter (PBS) and is introduced into another acousto-optic deflector (AOD2). AOD2 is driven at the same frequency, f_m , from DDS. The 1st order diffracted light by AOD2 is reflected back to AOD2 by a concave mirror (M1), and is re-entered into AOD2 to make 1st order diffraction light. The appropriate arrangement of this double-pass configuration makes a double frequency-shifted diffraction light with the frequency of $f_{lo}=f_L+2f_m$ which goes back to PBS along the entered light without angle change, used as a local beam (indicated by blue arrows). By using a combination of two quarter-wave plates (Q $\square$), PBS and a flat mirror (M2), the local beam is introduced into AOD1 collinearly with the signal beam, and is deflected to the same direction as the signal beam with the frequency at $f_{lo}'=f_L+3f_m$. At the remote end, PD1 detects both signal beam at f_s and the local beam at f_{lo}' , and the beat note frequency $f_b=f_{lo}'-f_s=f_L+3f_m-(f_L+f_m)=2f_m$ is achieved which is independent of laser frequency, f_L . After amplified and band-pass filtered, the frequency of the beat signal, $2f_m$, is counted by a universal counter (Agilent 53132A), and is recorded by another PC.

3. RESULTS AND DISCUSSIONS

3.1 Spatial Resolution

When AOD is used as a beam positioning scanner, the spatial resolution is defined by the total number of resolved spot N , which is the ratio of total scan angle $\Delta\theta$ to the divergent beam diameter $\Delta\phi$

$$N = \frac{Dq}{Dj} = \left(\frac{Df_a}{V_a} \right) / \left(\frac{l}{D} \right) = \frac{Df_a D}{V_a l} \quad (2)$$

where Δf_a , λ , D , V_a are the acousto-optic bandwidth, optical wavelength in the air, deflector aperture and the acoustic velocity in the crystal, respectively. N is determined by the parameters of AODF itself, and cannot be improved by the optical system. The number of N is less than a few hundred, and in order to overcome this optical resolution limit, we use the frequency counting as shown in Fig.3. In scanning the driving frequency f_m , the deflected beam at the remote end is moving across the photo detector with a diffracted beam diameter. In scanning the deflected beam, the frequency of the deflected beam is recorded while the detected DC power of PD is above certain threshold. The mean value of two frequencies at both edges is thought to be the frequency of the deflected beam whose beam center is just on the PD.

Figure 3. The center frequency f_c is determined from the mean value of the frequency at both edges, f_1 and f_2 . Red circle is deflected beam, and black circle is PD.

3.2 Experimental results

For determining the center frequency of the scanned light, the power of the scanned deflected beam should be constant. Since the diffraction efficiency of AOD depends on the modulation frequency of f_m and the applied rf power P_m , the

power of deflected beam is continuously changed while scanning. The applied rf power can be controlled by using a voltage-controlled attenuator (VCA) placed before the power amplifier. The appropriate applied rf power is preset in the PC1, and the modulation frequency and the control signal to VCA are synchronously sweeping by using PC1 so as to keep the diffraction efficiency constant (see Fig.2). In scanning the modulation frequency from 75 MHz to 85 MHz, the diffracted power decreases from 1.5 mW to 0.7 mW, whose power fluctuations are suppressed within 15 % after the power control scheme is activated. The preliminary result of our positioning system is presented. The remote PD is located 12-m apart from the AOD. The N number of AOD1 is 108 and the optical spatial resolution limit is 2.27 mm at the remote end. The input power to this system is 0.7 mW, and the modulation frequency, f_m , is swept by 500 kHz in 100 s. The position measurement is performed at two points, A and B, which are 2.27 mm apart in the vertical plain to the deflected beam. The frequency difference between point A and B is 0.43 MHz, which corresponds to 2.12 mm. Therefore the position of the remote PD can be determined within the error of 0.15 mm, which shows that the spatial resolution of this method is 15 times higher than that of the optical limit ($N=108 \rightarrow 1666$).

3.3 Discussions

In the above experimental result, the spatial resolution is limited by the determination accuracy of the center frequency, which will be improved by active intensity stabilization of the deflected beam. The theoretical angle resolution of the deflected beam is determined by the resolution of the frequency count. For example, $N=1666$ can be obtained by the frequency counting resolution of 30 kHz, and counting resolution is limited by the signal-to-noise ratio of the beat signal and the gate time. According to the experimental results, the 10 kHz of counting resolution can be obtained by the PD detected power of 5 μ W. The gate time of frequency counting is limited by the scanning speed of the light, which should be further investigated experimentally. The beam scanning area (angle) can be controlled by the position of collimated lens L1 placed after AOD1. Since the optical N number is independent of the divergence of the deflected beam, the expanding the scanning area decrease the optical limit of the spatial resolution (beam diameter is also expanded). On the other hand, the spatial resolution limit of the frequency counting method is constant as long as the frequency counting resolution is high enough.

4. CONCLUSIONS

We have proposed the novel satellite positioning system which consists of the laser, AOD and frequency counting. Compared with the conventional method, our proposal has the advantages of its compactness, no mechanical movement, fast scanning, and high angle resolution. In our preliminary experiment, the angle resolution is much higher than that of the optical resolution limit, which corresponds to the N number of 1666. We plan to apply this technique to the initial alignment of the 3 S/Cs to form the equilateral triangle-shaped interferometer with the arm length of 1000 km for the space gravitational wave detector DECIGO. Further investigations are necessary to test the actual performance and practicality before applying to DECIGO.

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