Status of frequency dependent squeezing experiment at TAMA

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(Dated: February 10, 2020)

Quantum noise of second generation ground based gravitational wave detectors is expected to be a limiting noise at almost the whole detection band. Frequency dependent squeezing is proposed to have broadband quantum noise reduction not only in the current generation detectors but also in the next generation. To produce frequency dependent squeezing, we need to reflect a frequency independent squeezing off a detuned Fabry Perot cavity, which is usually addressed as filter cavity. Besides, to counteract the quantum noise behavior of current generation gravitational wave detectors, the linewidth of filter cavity is chosen to be around 60Hz. In TAMA infrastructure(NAOJ), we developed a squeezed vacuum source which can produce 6dB squeezing and 14dB anti-squeezing. The squeezing ellipse rotation was achieved around hundred Hz region with 3dB squeezing at high frequency and reaching shot noise at low frequency by using a 300 meter filter cavity.

I. INTRODUCTION

The gravitational wave event GW150914[1] ushered in the era of gravitational wave astronomy with its coincident detection done by the two detectors of Laser Interferometer Gravitational-wave Observatory(LIGO). With the join of Advanced Virgo detector, GW170817[2] was localized much more precisely and benefit from this, this event was quickly associated with its electromagnetic counterparts. This event heralded the beginning of multi-messenger astronomy.

Apart from these two ground breaking events, there are many more others are detected[3]. Nowadays normal detection is actually the efforts of global collaboration after decades of instrument developments with example of advanced LIGO[4], advanced Virgo[5] and KAGRA[6]. However, to fully exploit this new window of the universe, there are proposals to improve current detectors and construct new facilities.[7][8] Among them, the implementation of filter cavity to achieve frequency dependent squeezing is considered to be a crucial solution to reduce quantum noise.

Quantum noise comes from the quantum nature of light, which impacts gravitational wave detector through the coupling of vacuum field from output port of interferometer.[9] In semi-classical picture, quantum noise shows up through two processes because of the quantization of energy exchange. One is the optical power absorption process done by photodiode, the other is the optical pressure exerted on suspended mirrors. Except for these two processes, we can always consider field as a electromagnetic wave so we call this semi-calssical picture. As a result, the laser light itself gives a fundamental limit for the signal readout.

Although we can not avoid the fundamental quantum property of light, there is way to introduce correlation between photons [10] and then we can use it to reduce detector's quantum noise.[11] The correlation between photons can be converted to continuous variable picture, and in this case, we could see clearly the quadrature amplitude is reduced in one axis while increased in the other. This is why this quantum state is always called squeezed states or simply called squeezing. The fact that we cannot reduce two orthogonal quadratures simultaneously is due to the Heisenberg uncertainty principle. [12] Unfortunately, these two quadratures correspond to the two ways quantum noise coupled into interferometer so at the first glance, we would say we cannot reduce both components of quantum noise at the same time. However, the low frequency quantum noise is dominated by one coupling way, which is called radiation pressure noise. While the high frequency quantum noise is dominated by the other coupling way, which is called shot noise. Although we cannot reduce both quadratures of squeezing, as proposed by Kimble[13], a squeezed state manipulated to be squeezed in one quadrature at low frequency and squeezed in the other quadrature at high frequency can be achieved, which is usually called frequency dependent squeezing.

The generation of squeezing can be achieved by the degenerate parametric down-conversion in a non-linear crystal hosted by a cavity. [14] A suitable squeezing

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source should be highly squeezed continuous-wave at the detector working audio frequency and in a well defined optical mode so that it can continuously provide noise reduction and couple well into interferometer. However, the audio frequency squeezing is easily polluted by coherent control field and back-scattering noise which makes it difficult to produce highly squeezed vacuum. Even in this case, 9dB of audio squeezing source[15] and 11dB of audio squeezing source[16] are produced in different labs.

The rotation of squeezing ellipse can be generally achieved by reflecting frequency independent squeezing off a filter cavity. This rotation means the quantum noise fluctuation projected to a certain fixed phase of local oscillator will experience a change from its original fluctuation to minimum/maximum and back to this original fluctuation when it goes across the whole detuned peak of the filter cavity. The difficulty of achieving low frequency squeezing rotation comes mainly from the intracavity loss and mode matching.[17] A hundread meter scale stably operated filter cavity is proposed to tackle these problems.[18]

Here I report the status of the frequency dependent squeezing experiment, including the development of frequency independent squeezing source and the recent progress of squeezing ellipse rotation by using a 300m filter cavity.

II. EXPERIMENT OVERVIEW

Our squeezer is based on the design of GEO 600. We have three 1064nm laser sources, which are used for main laser, OPO length control auxiliary laser and coherent control auxiliary laser separately. The phase lock loop(PLL) between main laser and auxiliary laser is realized by a fiber based optical set up with commercial phase detector and customized analog filters. The main laser light is separated into five parts and used for second harmonic generator(SHG), bright alignment beam(BAB) and local oscillator for two PLLs and balanced homodyne detector(BHD). The generated 532nm light from SHG is seperated into two parts. One is used to lock main laser with filter cavity while the other is used to pump optical parametric oscillator(OPO). The generated squeezed vacuum from OPO is injected into filter cavity via a suspended telescope and the reflected frequency dependent squeezed state is extracted by a Faraday isolator and sent to BHD to be characterized.

The goal of our experiment is to produce 9dB of frequency independent squeezing and achieve 4dB frequency dependent squeezing below rotation frequency and 6dB above.

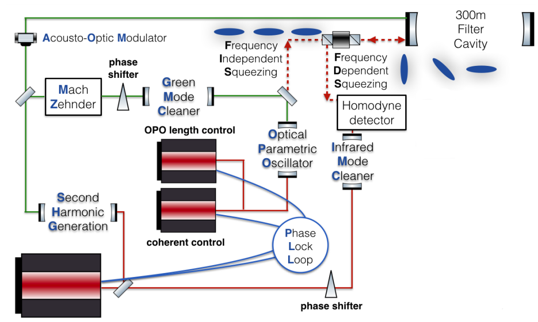

FIG. 1. This scheme shows the working principle of our system. Apart from the key components introduced above, there are also Mach-Zehnder interferometer to adjust and stabilize green power and mode cleaners to clean beam shape and reduce phase noise. There is also an AOM, which is used to change the frequency difference between green and squeezing in order to set the detuning of filter cavity

III. FREQUENCY INDEPENDENT SQUEEZING SOURCE

Squeezing is generated from the polarization effect of a nonlinear crystal, which is $P(\varepsilon) = \epsilon_0(\chi^{(1)}\varepsilon + \chi^{(2)}\varepsilon^2)$. The incident fields are 2ν pump field and vacuum which permeates the whole frequency spectrum. Since we want to have degenerate parametric down conversion, we care only about ν vacuum in this case. So we can have incident field as

$$\varepsilon = A_{vacuum} \cos(\omega t + \phi) + A_{pump} \cos(2\omega t) \tag{1}$$

The interaction of above equation with crystal is equivalent to take equation 1 into the polarization equation. As a result, the induced second-order polarization component will have ν frequency component and interfere with the same frequency component of the first-order polarization. When the phase matching is achieved, squeezing will be generated. However, squeezing can be degraded by loss and phase noise. Loss is equivalent to power loss caused by absorption or scattering while phase noise is caused by OPO length noise or coherent control loop locking noise. The impact of them is exerted on squeezing is

$$V_{\pm} = (1 - l)(R_{\pm} \cos^2 \theta + R_{\mp} \sin^2 \theta) + l \tag{2}$$

Here, V is the observed squeezing which has already been degraded, l is loss, θ is RMS value of phase noise, R is the generated squeezing inside OPO and plus/minus represents anti-squeezing/squeezing. By measuring squeezing and anti-squeezing level at different and using equation 2, we can infer the information of loss and phase noise.

We have achieved 6dB squeezing and 14dB anti-squeezing down to 10Hz. This is a decently good starting point to acquire frequency dependent squeezing.

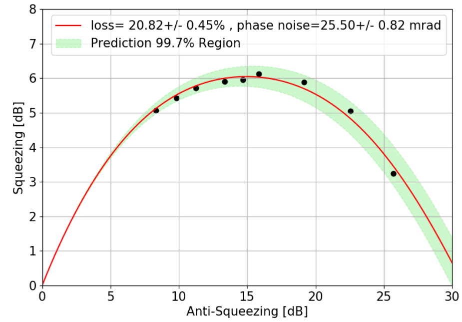

FIG. 2. We measured squeezing and anti-squeezing level with pump power from 20mW to 60mW with an interval of 5mW. These points are fit with equation 2 to give us loss of 20.82 percent and phase noise of 25.5mrad

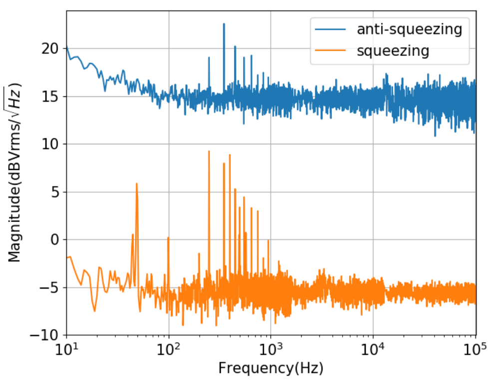

FIG. 3. Squeezing spectrum with frequency below 50Hz contaminated by back-scattering and beam pointing noise

IV. SQUEEZING ELLIPSE ROTATION AROUND 100HZ REALIZED BY 300M LONG FILTER CAVITY

Gravitational wave signal resides in phase quadrature of interferometer's output signal because of the differential property of gravitational wave. The low frequency dominating quantum noise, radiation pressure noise, is present because of the ponderomotive effect from suspended mirrors. This effect transfers quantum uncertainty from amplitude quadrature to phase quadrature and decrease with frequency. So we need to provide amplitude squeezing at low frequency. The high frequency quantum noise is directly from the phase quadrature quantum uncertainty. So we just need to have phase squeezing at high frequency.

To prepare a proper frequency dependent squeezing, we need to know how quantum noise change from shot noise dominated to radiation pressure noise dominated. One important quantity is Ω_{SQL}, which is the frequency these two noises have the same level. In the case of advanced detectors, this frequency is defined as

$$\Omega_{SQL} = \frac{t_{sr}}{1+r_{sr}} \frac{8}{c} \sqrt{\frac{P_{arm}\omega_0}{mT_{arm}}} \tag{3}$$

Here, P_arm is the arm cavity power, ω_0 is carrier frequency, m is the mass of test mass, T_{arm} is the transmissivity of arm cavity input mirror, t_{sr} and r_{sr} are amplitude transmissivity and reflectivity of signal recycling mirror.

At this frequency, squeezing ellipse needs to be oriented at 45 degree. Besides, the change from shot noise to radiation pressure noise should be the same with the change from phase squeezing to amplitude squeezing. This sets the requirement of filter cavity detuning.[19] According to this requirement, we choose our filter cavity linewidth to be 58Hz and detuning to be 54Hz.

The frequency dependent rotation is induced by the phase regulation done by filter cavity since we know that the reflected light from an optical resonator will experience a phase change of 360 degree by passing through the resonance of it. The correlation built by squeezing source will be arranged and then we have a new correlation inside the linewidth of filter cavity.

The detuning can be easily set but it is important to see the effect which is the filter cavity can rotate maximum anti-squeezing to be squeezing. The difficulty is this squeezed field which enters filter cavity will experience decoherence and degradation[19]. Up to now, we can rotate it close to shot noise.

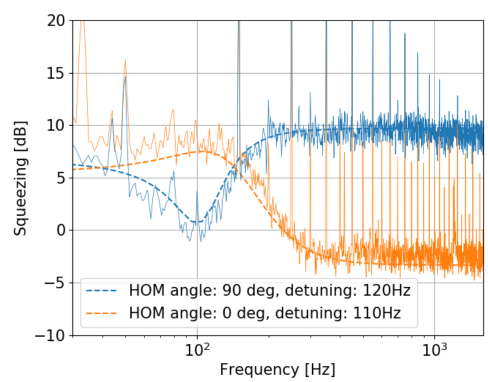

FIG. 4. Frequency dependent squeezing with detuning around 100Hz. Comparing this with figure 3, we can see the effect of filter cavity

V. CONCLUSION

We have developed a squeezing source which can generate 6dB of squeezing and 14dB anti-squeezing. We need to reduce both loss and phase noise by a factor of 2 to achieve our goal. By injecting this squeezing field into filter cavity, we achieved squeezing ellipse rotation around

100Hz. 3dB squeezing is achieved above the rotation angle while shot noise level is achieved below rotation frequency. We will further reduce the decoherence and degradation sources value to achieve more squeezing espically at low frequency.

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