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LIGO SURF 2024:Interim Report I — Vacuum Beam Guide for Quantum Communication

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Contents

1 Introduction

Quantum communication is anticipated to be a cornerstone of future transmission technology[1], necessitating optimal solutions for long distance transmission at a continental scale. Although optical fiber cables have revolutionized communication, they exhibit significant photon losses due to absorption $\sim 10^{-1}$dB/Km [4], posing challenges for quantum communication[5]. For a system utilizing continuous-variable quantum communication, loss becomes a crucial parameter to control. For example, in optical squeezing, losses dictate the maximum squeezing levels, as discussed in the supplementary material of [6] by Goodwin-Jones et al.

$$S = S_0(1 - l) + l, \tag{1}$$

where S_0 denotes the ratio of squeezing to vacuum variance before the loss occurred, S is the ratio after the loss occurred, and l denotes the fractional power loss in the system.

Two primary methods proposed to address these challenges are satellite-based communication and quantum repeaters. Nicolas Sangouard et al. discuss a quantum repeater strategy utilizing atomic ensembles as quantum memories [7]. Meanwhile, Sumit Goswami et al. propose a network of low Earth orbit (LEO) satellites with total estimated losses of less than 30 dB over 20000 km, that is $\sim 10^{-3}$dB/km, provided that each satellite, separated by 120 km, maintains other losses below 2% and employs 60-cm diameter telescopes to eliminate diffraction loss [8].

Another innovative approach, presented by Yuexun et al. [5], involves a vacuum beam guide (VBG). This method uses an array of lenses to guide light through a vacuum pipe, enabling long-range quantum communication over thousands of kilometers with a quantum channel capacity exceeding 10^{13} qubits/sec. Using this methodology, we can limit the losses to $\sim 10^{-4}$dB/km making it the best quantum communication method over long distances. Photon losses in the VBG arise from three factors: lens losses, residual gas absorption, and imperfect alignment, collectively represented as[5]:

$$\alpha_{\text{total}} = \alpha_{\text{lens}} + \alpha_{\text{gas}} + \alpha_{\text{align}} \tag{2}$$

Lens loss, denoted as α_{lens}, results from absorption, scattering, reflection, and diffraction. Proper lens radius selection minimizes diffraction loss, and multi-layer anti-reflective coatings reduce lens losses to less than 10^{-4} dB/km at wavelengths around 1550 nm. Gas loss within the VBG, primarily due to absorption by residual air at 1 Pascal pressure, also remains below 10^{-4} dB/km at similar wavelengths. Imperfect alignment in the confocal design contributes to the effective attenuation rate, expressed as[5]:

$$\alpha_{\text{align}} \leq \frac{-10}{L_0} \log_{10} \left(1 - \frac{2\sigma^2}{w_0^2} - \frac{\sigma^2 L_0}{L_0^2} - \frac{\sigma^2 f}{f^2} \right) \tag{3}$$

where σ_s and σ_{L_0} represent transverse and longitudinal displacement fluctuations, respectively, and σ_f indicates focal length deviation.

2 Objective

This study aims to understand the evolution of the beam as it passes through a VBG that can connect the west coast of the U.S.A. to the East coast. To understand the behavior over 4000kms, we can take a fraction of it, $\sim 300kms$, and put lenses $\sim 6Kkms$ apart. Using Finesse 3 software, we will simulate the lens array and optimize the parameters such as lens diameter, focal length of lens, and lens distances. Additionally, we will explore control mechanisms in four dimensions, considering whether active control or seismic isolation is necessary and the extent of isolation required. This project will give a strong foundation for further development of the vacuum beam guide for quantum communication.

2.1 Applications and Use Cases of Vacuum Beam Guides (VBG)

The Vacuum Beam Guide (VBG) presents numerous potential applications and use cases, especially in the realm of secure communication channels. One of the primary applications of VBG is in establishing secure communication links over continental distances, which is particularly valuable for the finance and trading sectors. In these fields, the transmission of sensitive data with minimal risk of interception or loss is paramount, and the use of VBG can significantly enhance the security and reliability of these communications. [3]

A study by Gottesman et al. (2012) [2] highlights the potential of quantum repeaters for extending the baseline of telescopes using quantum communication channels. By employing VBGs, similar benefits can be achieved, but with the added advantage of low photon noise.

The Vacuum Beam Guide (VBG) presents significant potential for enhancing long-baseline interferometry, a technique crucial for achieving high-resolution observations in astrophysics and geophysics. Baseline interferometry involves the use of multiple telescopes or antennae separated by large distances to effectively simulate a much larger aperture, thereby increasing the resolution and sensitivity of the observations. Traditional baseline interferometry relies on satellite links or terrestrial communication networks to combine signals from widely separated telescopes. These methods, however, often introduce noise, latency, and potential data loss, which can degrade the quality of the combined signal. VBGs offer a solution to these issues by providing a stable, low-loss transmission medium. This stability is particularly important for maintaining the phase coherence of the signals, which is essential for the accurate combination of data from different telescopes. [2]

3 Approach

Our approach begins with simulating different aperture sizes to understand the behavior of the electric field as light propagates through the array. Serrated apertures are known to mitigate phase noise in gravitational wave detectors, we will explore their use in the vacuum beam guide. Upon comprehending the electric field behavior under various parameters, we will focus on optimizing the VBG for low loss and cost-effectiveness. Cost optimization will consider factors such as beam tube steel, lens substrate and coatings, lens mounts, and vacuum pumps. Low-loss optimization will address lens aberrations, clipping, and misalignments.

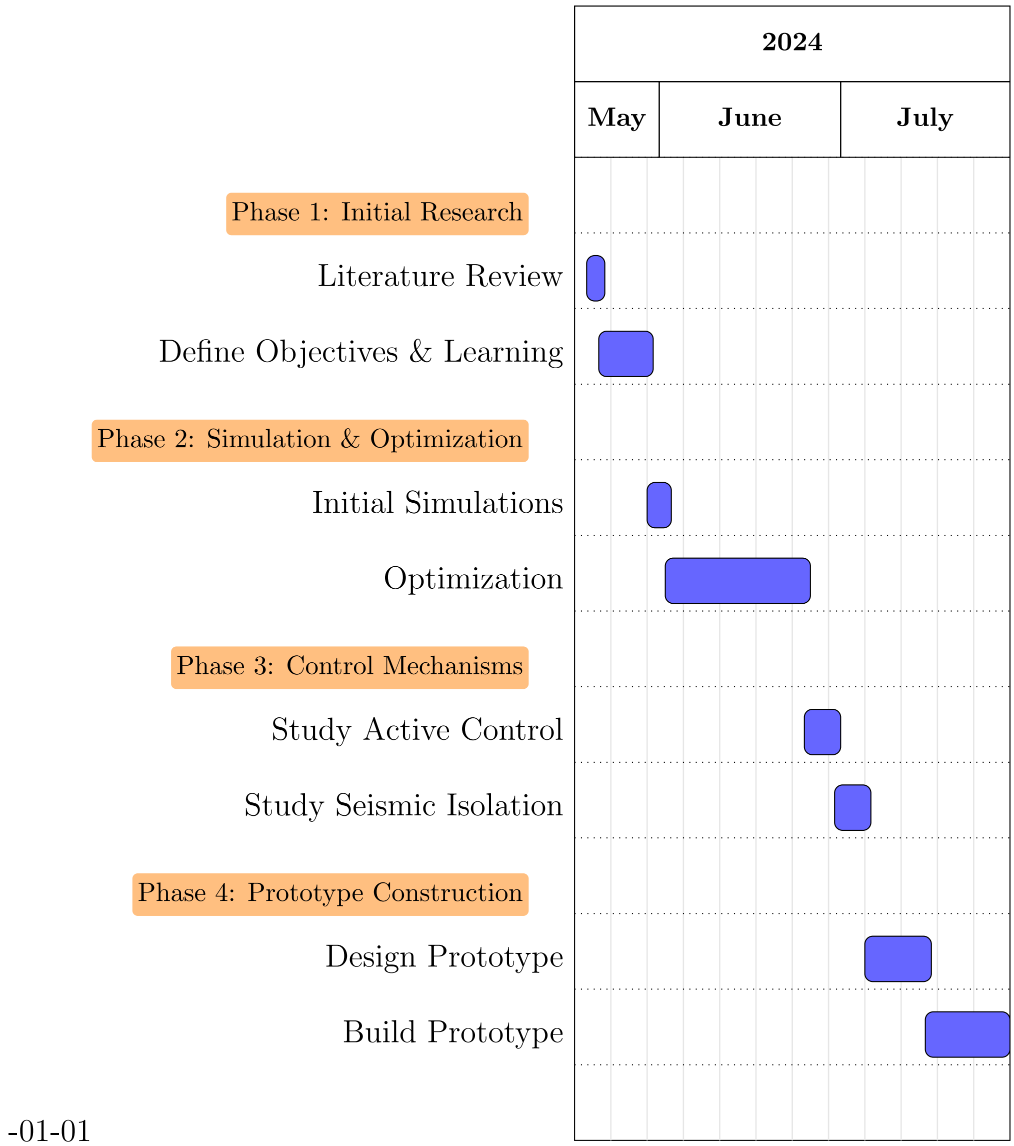

Figure 1: Project Timeline

The control problem involves managing four degrees of freedom that include pitch and roll axis for angular control and non-azimuthal directions for translational degrees of freedom at each lens to maintain beam centering within ± 1 cm. We'll also explore whether active control is necessary for the lens mounts. Additionally, a key aspect of the project involves constructing a prototype for testing in the Caltech tunnels. This will enable us to conduct quantum experiments and compare the results with our simulations.

4 Update on the Work Done

I have understood the Finesse 3 software sufficiently to meet the project requirements. I have taken a training course on Finesse. The course gave me an understanding of the capabilities and importance of Finesse in Gravitational Wave detector science, along with an understanding of the Syntax of Finesse 3. Building on this foundation, I built a preliminary model to simulate the lens array with 20 lenses. In these simulations, I modeled the Gaussian beam and calculated the total electric field before each lens in the array. The resulting plots provide insights into how the electric field behaves along the array for different lens diameters. Furthermore, changes in the focal length of the lenses introduce notable variations in photon losses along the array. In parallel, I also worked on learning the Gaussian optics, beam parameter, and how this single parameter "q" which is a complex number, can give all information about the beam at a node.
We can write

$$E(t,x,y,z) = \sum_j \sum_{n,m} a_{jnm} u_{nm}(x,y,z) \exp\left(i(\omega_j t - k_j z)\right), \quad (9.1) \tag{4}$$

with u_{nm} as special functions describing the spatial properties of the beam and a_{jnm} as complex amplitude factors (ω_j is again the angular frequency and $k_j = \omega_j/c$).

The beam parameter q is a complex quantity defined as [9]

$$q(z) = \frac{1}{R_C(z)} - \frac{i\lambda}{\pi w^2(z)}, \tag{5}$$

Other parameters, like the beam size and radius of curvature, can be written in terms of the beam parameter q: [9]

$$w^2(z) = \frac{\lambda}{\pi}|\mathrm{Im}(q)|^2, \tag{6}$$

$$w_0^2 = \frac{\mathrm{Im}(q)\lambda}{\pi}, \tag{7}$$

$$z_R = \mathrm{Im}(q), \tag{8}$$

$$R_C(z) = \frac{|q|^2}{\mathrm{Re}(q)}. \tag{9}$$

Along with this, understanding the photon loss along the array based on the lens radius also explains how power changes in lens radius can majorly affect the photon losses in the lens array as shown in fig:2. The evolution of the beam parameter along the array is governed by the ABCD matrices. This transformation, resulting from the introduction of an optical element, can be succinctly described by four real coefficients

$$\frac{q_2}{n_2} = \frac{A\frac{q_1}{n_1} + B}{C\frac{q_1}{n_1} + D}, \tag{10}$$

with the coefficient matrix

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix}, \tag{11}$$

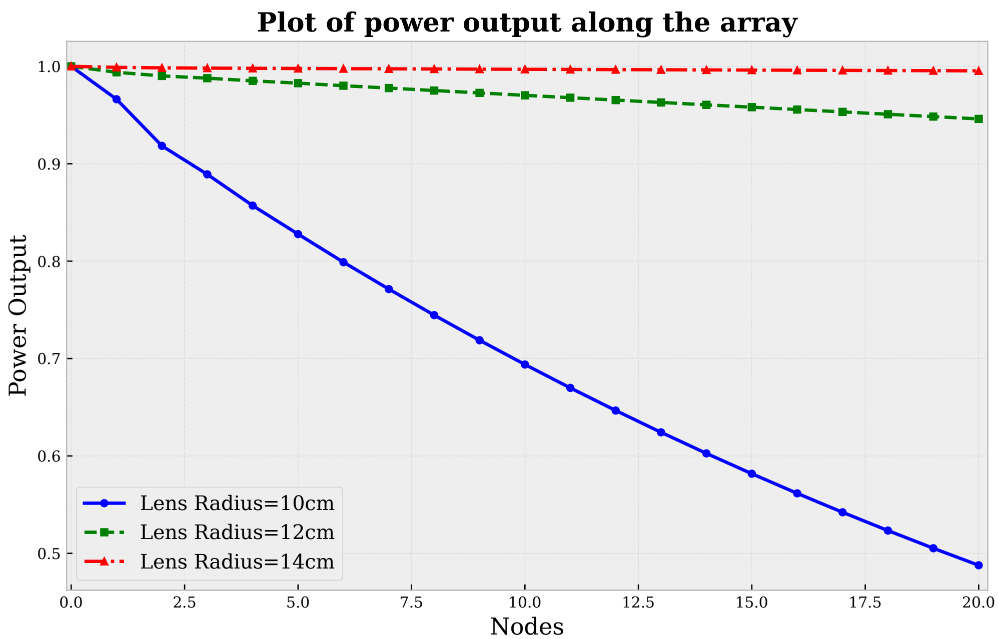

Figure 2: Plot of power output along the array

n_1 being the index of refraction at the beam segment defined by q_1, and n_2 the index of refraction at the beam segment described by q_2 [9].

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