Holographically corrected telescope for high bandwidth optical communications

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Abstract

We present a design for an optical data communications receiver/transmitter based on the holographic correction of a large diameter, poor-quality, reflecting primary. The telescope has a high signal to noise ratio (>60dB) and narrow bandwidth (<0.5nm) and is scalable to meter class apertures. In this paper we demonstrate the correction of a reflector telescope with over 2000 waves aberration to diffraction limited operation, capable of handling data transmission rates up to 100GHz.

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1. Introduction

In optical data communications, the power of the received signal, P_r can be expressed as a function of the transmitted power, P_t by[1]

$$P_r = P_t \times L \times G_t \times G_r \times \eta_t \times \eta_r \tag{1}$$

where L is the transmission loss (including pointing error and free space propagation losses) and G_t, G_r and η_t, η_r are the transmitter and receiver gains and efficiencies respectively. For a given transmitter power, the size and quality of the optical components used will dramatically affect the last four quantities, and the resulting signal to noise ratio (SNR). Increasing the diameter of the transmitting or receiving optics will improve the SNR, but this may require a trade-off in the surface quality of these components, decreasing the efficiency of the system. In this paper, we present a scheme whereby low-quality, large diameter mirrors are holographically corrected to diffraction limited performance over a narrow bandwidth. As well as reducing construction and deployment costs by orders of magnitude over conventional designs, these schemes incorporate holograms which act as filters to increase signal to noise ratios.

The basic scheme for the holographic correction of an aberrated reflecting primary is shown in Figure 1, with various alternative configurations discussed in previous work[2-9]. A distant source of laser illumination is incident on an aberrated primary mirror, with the focused light gathered by a secondary element, which forms a demagnified image of the mirror surface onto the plane of the hologram [Fig. 1a]. A hologram is recorded between this beam and a diffraction limited, plane wave reference beam. On replay, a distant modulated laser signal is incident on the primary once more to recreate the object beam [Fig 1b]. At the hologram this beam reconstructs the original reference beam, with the modulation of the source beam retained. In this way a large aberrated element can be used for its large light gathering and resolution, with correction provided by a small, inexpensive holographic element.

2. Experimental evaluation

In order to evaluate the performance of a holographically corrected telescope system, we used a similar set-up to the one shown in Fig. 1. Collimated light, produced with a diffraction limited, parabolic mirror (*D* = 200mm, *f* = 1m) was directed onto an aberrated spherical primary (*D* = 200mm, *R* = 1m). The 4mm thick, aluminum-coated, glass spherical mirror had more than 2000 waves figure error and 47 waves of spherical aberration. The reflected light was directed by a pick-off mirror to a camera lens (*f* = 50mm, F/1.4) which produced a 20mm diameter image of the surface of the aberrated mirror onto holographic film. A hologram was recorded with a diffraction limited, plane wave reference beam incident on the plate from an angle of approximately 40^{o}. The phase holograms were recorded using a CW, frequency-doubled Nd:YAG laser (λ = 532nm) on Agfa 8E56 plate film. A typical diffraction efficiency of 70-90% was obtained.

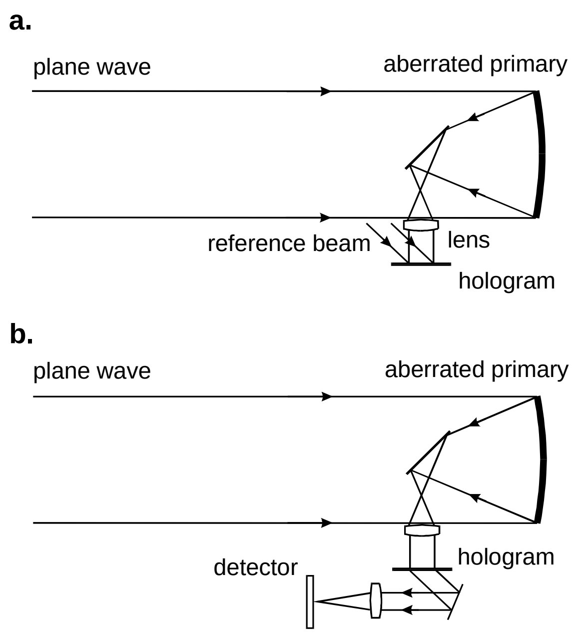

Fig. 1: a. Recording. Collimated laser light reflects off the mirror and through secondary optics to combine with a reference beam to write the hologram. **b.** Replay. The same collimated light wave will pass through the system to reconstruct the reference beam.

After processing, the hologram was returned to the recording position for reconstruction. With the collimated light again reflected off the aberrated mirror and through the secondary optics onto the hologram, the original reference beam is reconstructed. The fidelity of this reconstruction was measured by observing both the focused spot size, as well as the interference pattern against a diffraction limited plane wave. Figure 2 shows the complete removal of more than 2000 waves (as evidenced by the uncorrected focal spot) to a reconstructed wavefront error of ~0.1λ.

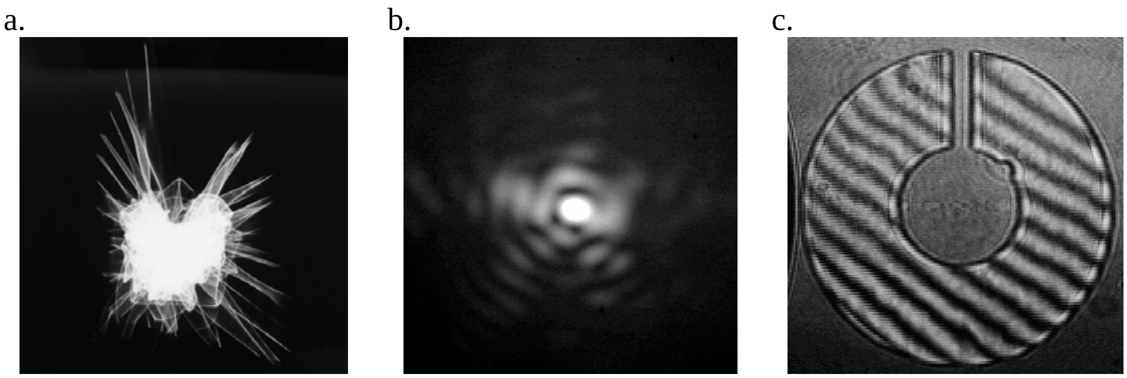

Fig. 2: Reconstruction analysis. **a.** The uncorrected focal spot (vertical dimension of box ~45mm). **b.** A magnified image of the focal spot of the reconstructed beam (vertical dimension of box ~100μm). **c.** Interferogram of the reconstructed reference beam demonstrating correction to $\lambda/10$.

The hologram is a record of the phase error of the mirror aberrations at the wavelength of the recording laser, so if the reconstruction wavelength is different from the write beam wavelength, some wavefront aberration will remain. If an aberrator induces a phase distortion of ϕ_1, then the remaining phase error after correction (with no change in the geometry of the system) is $\phi_2 = F\phi_1$, where F is the wavefront correction factor given by;

$$F = \frac{|\lambda_1 - \lambda_2|}{\lambda_2} \qquad (2)$$

with recording and reconstruction beam wavelengths, λ_1 and λ_2 respectively.

As well as the increase in wavefront aberration in the reconstructed beam at other wavelengths, there will also be a change in the angle at which these signals are diffracted from the hologram. The combination of these two effects can be observed in Figure 3 where an image has been produced by focusing the reconstructed beam with a 200mm lens onto photographic film with the reconstruction wavelength varied over a range of 80nm using a Coherent Infinity XPO laser.

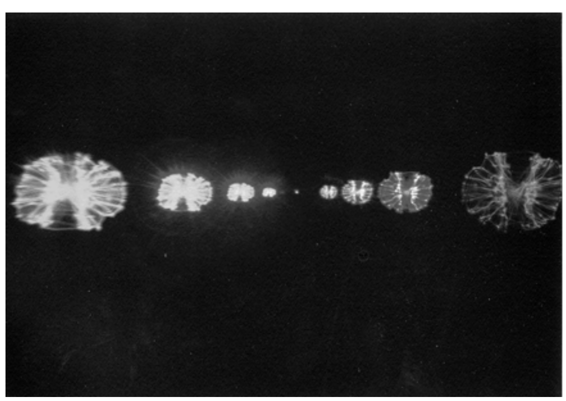

Fig. 3: Broadband operation. The spots produced at wavelengths ±40nm, ±20nm, ±10nm, ±5nm (from outside in) from the central wavelength of 532nm (center). The center to center separation of the two outer spots is 26.5mm.

This spatial displacement of aberrated, off-wavelength background emissions can be used to extract a signal wavelength with high signal to noise. Using a pinhole (or fiber input) centered on the focal position of the recording wavelength, the transmitted power can be restricted to a very narrow bandwidth with a definite cut-off wavelength.

The filtering bandwidth in our set-up was determined by placing a 100μm pinhole at the focus of the 200mm lens, with the power detected on the other side measured as a function of wavelength. The plot, shown in Figure 4, has a FWHM of 0.5nm, which matches the linewidth of the laser emission, indicating that the actual response function of our telescope is better than this. By modeling the change in position and size of the focal spots in Figure 3, we can estimate that by using a 30μm pinhole/fiber the receiver response function would have a FWHM of ~0.1nm and a cut-off bandwidth of <0.2nm. As an indication of the SNR, the amount of Argon-ion laser power (λ = 514nm) which leaked through the 100μm pinhole (due to scatter from the holographic film) was measured to be >60dB below the signal strength. Improvements in the design could further increase the rejection of light at other wavelengths.

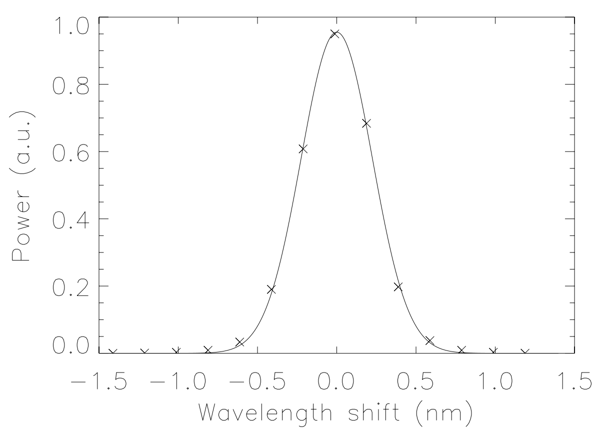

Fig. 4: Narrowband response. The power of a reconstructed signal beam focused through a 100μm limiting aperture is plotted as a function of wavelength difference from the recording wavelength of 532nm.

In order to examine the effect of the holographically corrected receiver on a modulated signal beam, we used a train of 170ps mode-locked pulses from a frequency-doubled, Q-switched, Nd:YAG laser to simulate a beam with a high frequency modulation. The “transmitter” in this case was the parabolic primary used in writing the hologram and the “receiver” was the holographically corrected telescope. It should be noted, however, these roles could be reverse, with the corrected telescope be used as a transmitter, by using a modulated, phase conjugate reference beam, incident on the hologram, as the signal. The temporal profile of the pulses was measured before and after transmission through the receiver/transmitter pair. The two pulse shapes matched to within 5ps, suggesting that a 100GHz signal could be transmitted or received using the holographically corrected telescope, with no little effect on the signal.

3. Alternative configurations

In space, the simplest way to correct for a receiver would be to have a distance point source of laser light which is used in place of the collimated beam, since this would remove the requirement of a perfect collimator. This architecture is shown in Figure 5. If a collimated light source from a distant transmitter is used to reconstruct the hologram, there will be some residual aberration present due to the differing amounts of spherical aberration from recording to replay[6-8].

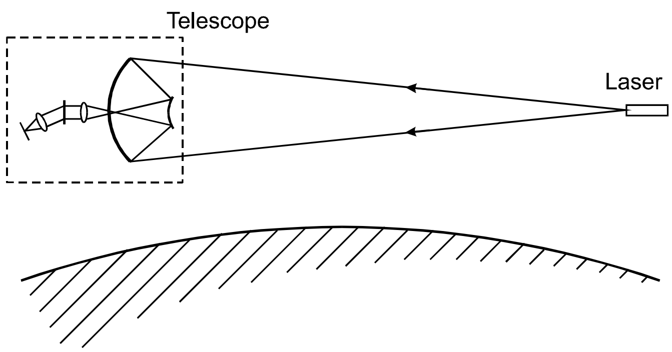

Fig. 5: Correction in space. In orbit, a distant beacon can be used as an illumination source to record the hologram, eliminating the need for a large perfect parabolic mirror for collimation.

The difference in 3rd-order spherical aberration for a point source at a distance *x*, compared to that of a point source an infinite distance away from a parabolic primary is given by:

$$W = \frac{(y - f)\rho^4}{8 f^2 y^2} \tag{3}$$

where f is the focal length of the mirror, and ρ the semi-diameter. For a 2m diameter, F/0.5 primary, this means that in order to achieve correction to a tenth of a wave, the point source must be at least 2350km away, which is comparable to the separation required for a global coverage of communications satellites. In this way, a simple correction scheme would involve a laser attached to one satellite acting as the beacon to correct for the aberrations in another. Once corrected each aberrated telescope could be used to both transmit and receive optical signals, with the simultaneous rejection of background light.

4. Conclusion

We have constructed a holographically corrected telescope suitable for optical communications. Our measurements have demonstrated that it has a high SNR and narrow bandwidth response, while causing minimal distortion to ultra-high frequency communications. The simplicity of this design, and its scalability to meter class apertures makes it ideal for an inexpensive global network of lightweight, optical communications satellites or for high-frequency data links with future interplanetary space probes.

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