Versatile phase stabilization technique for holographic recording of large aperture volume Bragg gratings

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ABSTRACT

We present a new method for phase stabilization of a holographic recording system for volume Bragg gratings. The primary feature of this method is that it is extremely flexible and simple to integrate into an existing holographic recording setup. The setup allows for Bragg gratings with arbitrary tilt and resonant wavelength to be recorded. An analysis of the effects of phase stabilization and a method for analyzing the effectiveness of this phase stabilization approach are also introduced and successfully demonstrate its benefits.

Keywords: Interferometry, phase measurements, holography. volume Bragg gratings

1. INTRODUCTION

Volume Bragg gratings (VBGs) are a widely used optical component for applications such as spectral shaping, communications, and sensing due to their ability to generate diffraction into a single order with high efficiency when the Bragg condition is met. VBGs are created by recording a spatially varying sinusoidal pattern inside a medium and are typically produced using holographic exposure, lithography, phase masks, or point by point inscription[1-3]. These methods apply most readily to VBGs written into optical fibers. For VBGs in a bulk medium with apertures on the order of several millimeters, holographic recording of a two beam interference pattern (Fig. 1) is the most suitable approach. This method can be used to create both reflecting and transmitting type VBGs of different spatial frequencies by adjusting the recording angle of interference. To achieve high quality volume gratings with high-efficiency and periods as low as 200 nm, it is necessary to be able to generate a uniform modulation period throughout the volume of the medium together with high contrast refractive index modulation (RIM). As an example, for gratings being designed as output couplers for laser systems, it is usually necessary to achieve very specific spectral widths and angular selectivities in addition to precise diffraction efficiencies, making it critical to have exact control over the RIM[4]. The primary detriment to obtaining consistent fringe visibility, and therefore high-quality VBGs, is shifting of the interference fringes during the recording process. Such fringe movement could be due to vibrations of beam delivery optics or the sample, as well as localized changes in the relative density of air along the paths of the recording beams.

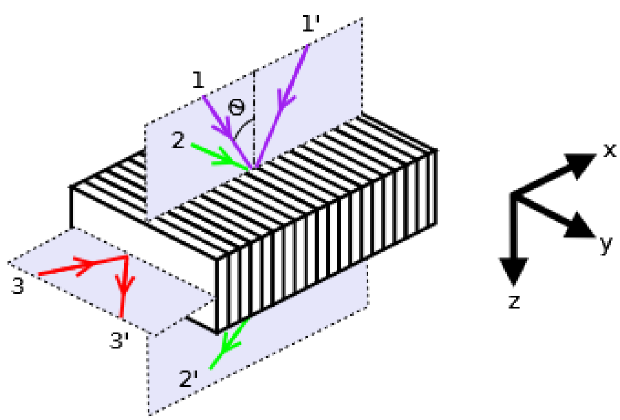


Figure 1. The general recording and read out for a VBG. Rays marked 1 (purple) indicate the recording wavelength which generates the interference pattern. After recording and development, the grating can be used as a transmitting grating at a different wavelength marked with 2(green) or at yet another wavelength the grating can be used as a reflecting grating indicated by 3 (red). Color online.

Practical Holography XXVII: Materials and Applications, edited by Hans I. Bjelkhagen, V. Michael Bove, Jr.,
Proc. of SPIE Vol. 8644, 864405 · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2005409

By measuring and controlling the relative phases in the recording beams, high visibility fringes can be maintained throughout the recording. The resulting VBG will have a consistent index modulation with efficient use of the material's dynamic range. To control the phase of the interference pattern, a number of different methods have been proposed[5-9]. The most common is the use of the dynamic grating formation, or through the use of an auxiliary grating, to diffract a portion of each recording beam into the other recording beam to generate an interference pattern[6,7]. This allows for direct monitoring of the relative shift of the interference pattern and the current grating structure. The drawbacks of this method include possible interference by reflections from the back surface of the medium. It also places restrictions on the recording medium to have low absorption at the recording wavelength and not introduce significant distortions into the beams. The material must also form a weak grating during the recording process. This may not always be the case when a latent image is formed and further development is necessary, or where the dimensions of the recording substrate are not able to produce a useful diffraction efficiency. So, while the use of a partially formed grating to diffract the recording beams into each other is applicable to some holographic recording setups, it lacks the flexibility necessary for recording gratings in a variety of materials. To address this issue, we propose a simple, flexible method for phase stabilization that can be applied to most common holographic recording setups with the potential for a factor of two increase in sensitivity. The method shares the same path as the recording beam but does not place any requirements on the recording medium. This method combines some of the aspects of the last system proposed by Guest[8] and the system by Muhs[9], but provides better flexibility and sensitivity to phase shifts.

2. THEORY

Before describing the method for stabilizing interference fringes, it is important to determine the effect of an uncontrolled fringe pattern. When using two beam interference to record a grating, as shown in Figure 1, the resulting grating is directly proportional to the two beam interference intensity pattern when operating within the linear region of the material photosensitivity curve[10]. This interference pattern is given by Eq 1,

$$I(x) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(2kx\sin\theta + \phi)\,, \tag{1}$$

where I_1 and I_2 represent the irradiance of each recording beam, and the resulting index modulation profile is proportional to the cosine with a period determined by the wavenumber of the recording beam and the angle of interference, θ. The term φ is the relative shift in phase between the two recording beams. Modification of any of the arguments in the cosine of Eq 1 will result in a shifting fringe pattern. The wavenumber is held constant and we assume that the angle of interference is stable at the arcsecond level such that no significant change in period occurs. In our setup this stability has been confirmed experimentally by measuring the angle stability of the recording mirrors by forming a Sagnac interferometer and monitoring the shifts of fringes. Practically speaking, this level of stability in angle is not difficult to achieve with commercially available optical mounts and a vibration-isolated table. The most significant effect on the interference pattern comes from changes in φ, primarily due to vibrations and air fluctuations. This results in a shifting of the relative phases between the recording beams as a function of time. The recorded interference pattern in this case is given by Eq 2.

$$I_{final}(x) = I_1 + I_2 + \int_0^T 2\sqrt{I_1 I_2}\cos(2kx\sin\theta + \phi(t))dt\,. \tag{2}$$

The effect of randomly varying phase difference about a mean value can also be calculated to determine a limit to phase noise allowable in a recording system. For this calculation we assume a randomly varying phase difference described by a Gaussian probability density function which will allow the effect on the fringe pattern to be described by a single parameter relating to the variance of the phase fluctuations. The probability density for a randomly distributed phase variation is shown in Eq 3:

$$W(\phi) = \frac{1}{\sqrt{2\pi}\sigma} e^{\left(\frac{-\phi^2}{2\sigma^2}\right)}, \tag{3}$$

where σ is the root means square error (RMSE) about the average phase value. The interference pattern can then be described by the integral in Eq. 4. Due to the ambiguity of a 2π phase shift, we assume that σ is significantly less than π.

This assumption is shown to be reasonable for the phase fluctuations that we measure in our setup and our calculated results show that any fluctuations that do not fulfill this criterion will result in a grating which is entirely washed out.

$$I_{final}(x) = I_1 + I_2 + \int_{-\pi}^{\pi} W(\phi) \cdot 2\sqrt{I_1 I_2} \cos(2kx \sin\theta + \phi) d\phi \tag{4}$$

The fringe visibility of the resulting interference pattern is the metric which will be used to determine the quality of the recorded grating. This value is a normalized indicator for the amount of the maximum possible index change that can be achieved:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{5}$$

Equation 4 was integrated numerically for a number of σ values to determine the effect of fringe shift on the effective dosage. The results are shown in Fig. 2 as a function of the fraction of a full recording wavelength shift. As the amplitude of the phase variations increases, the fringe visibility starts to decrease, resulting in a weakened RIM. The value of σ in radians can be determined from this axis by multiplying by 2π. The inset in Fig. 2 shows the region of minimal phase fluctuations in which we operate using phase stabilization. In this region the decrease of visibility is relatively slow and close to optimal RIM can be achieved if the fluctuation amplitude is less than 5% of a wavelength.

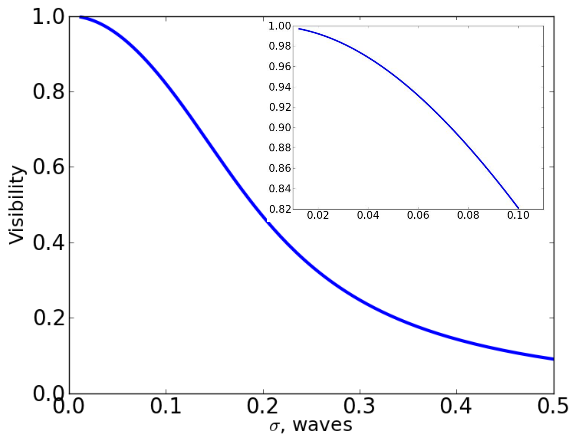


Figure 2. The decrease of visibility as the variation in phase fluctuations increases. Phase variation σ is shown as a fraction of the recording wavelength. Detail is shown on different scales in the inset.

3. SETUP

The proposed setup (Fig. 3) uses a small portion of the recording beam to measure the relative phase of the recording beams, while the rest of the beam is used for the recording. The portion of the beam used for phase measurement will be called the probe beam. The phase measurement is achieved through a corner cube retroreflector which is placed above the sample. The probe and recording beams trace along the same path to reach the recording plane and the probe beam is then reflected back along this path to double the relative phase deviations which are incurred. At the detector plane, the back-reflected probe light forms an interference pattern and the corner cube is adjusted in position to achieve overlap of the two collinear probe beams so that the entire beam diameter gives a zero fringe interference pattern. One of the primary benefits of this method is that the precision of this alignment can be very coarse. The retroreflector guarantees angular alignment and beam overlap can be achieved without the use of precision stages.

As the relative phases of the paths change, the irradiance at the detector will vary as Eq. 1 with θ=0. By using a retroreflector, the system can be easily moved and realigned for recording gratings of different period and arbitrary grating tilt angles. The detector signal is used as feedback and a piezo-electric transducer (PZT) is placed beneath one of the mirrors to correct for measured phase fluctuations by maintaining a constant detector signal.

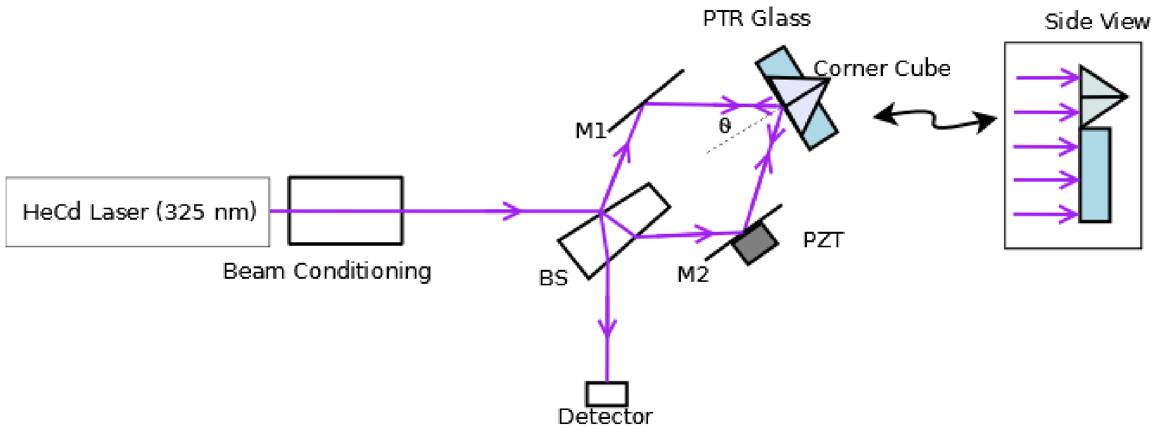


Figure 3. The VBG recording setup showing the paths of the recording/probe beam. The side view shows how the beam is split between a recording portion and a probe portion for measuring phase.

The phase difference in the recording beam can be calculated from the measured variations in the detector voltage. In order to determine the conversion factor between the detector's voltage and the probe beam phase difference, the PZT was driven with a ramp function to generate a sinusoidal variation in the detector voltage with a period corresponding to a phase difference in the probe beam of 2π as shown in Fig 4. By fitting a sinusoid to this curve, a conversion function was calculated to convert a detector voltage to a phase difference between the beams.

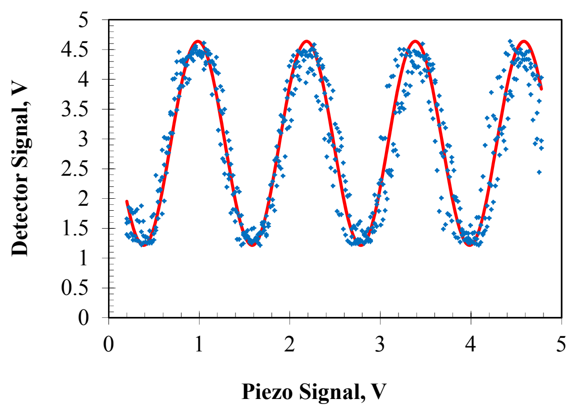


Figure 4. Ramping of the PZT voltage allows a shift in the detector voltage, centered about the DC level, to be converted to a fraction of a phase shift once the period is determined. Red line shows a fit to the experimental data in blue.

4. ANALYSIS

To test the effectiveness of this system, several volume Bragg gratings were recorded. The gratings are designed to be reflecting VBGs with a resonant wavelength of 978 nm and the time for each recording was 22 min. We expected to see an increased RIM due to increased fringe visibility in the phase stabilized recordings. In a reflecting VBG with high diffraction efficiency, an increased RIM will correspond to a higher bandwidth and the RIM can be calculated by matching measured spectral response to those calculated by theory. Before the exposure of each grating, the feedback signal was monitored so that the phase noise present in the recording environment could be determined. After exposure and development, the gratings were cut to a thickness of 3.75 mm and measured using a wavelength tunable laser. The transmission spectrum of each grating was used to determine the RIM induced in each recording.

The first grating was recorded with no stabilization present. Figure 5 shows the measured feedback signal before and during the recording, converted to phase difference using Fig 4. The relative phase of the beams has both high frequency noise and slowing drift in one direction. Using the Eq. 2 the best fringe visibility that can be achieved by recording in this condition is 80.7% of a perfect recording. The transmission spectrum is shown in Fig. 5. The refractive index modulation can be calculated based on knowledge of the spectral bandwidth and length of the grating. For a 3.75 mm thick RBG with resonant wavelength of 978, a 430 pm bandwidth corresponds to 490 ppm index modulation.

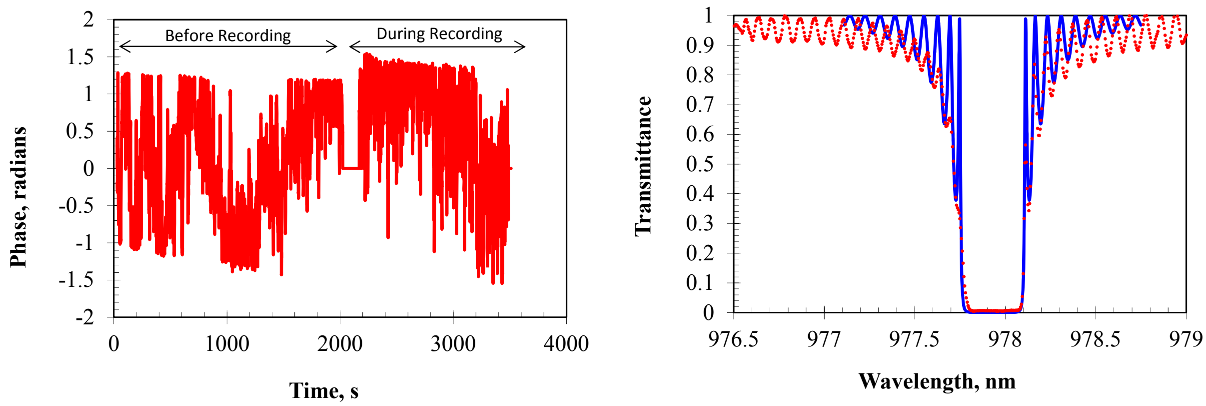


Figure 5. The recording of an unstabilized grating as a baseline. The relative phase of the recording beams (left) shows both high frequency noise and long term variations. The resulting transmission spectrum (right) of a 3.75 mm thick grating has a bandwidth of 430 pm FWHM.

A second RBG was recorded using the same parameters. During the recording process, the PZT was used to maintain a constant relative phase of the recording beams. Figure 6 shows the phase variations immediately before recording and during. The remaining noise has RMSE of 0.0052λ and the expected visibility of this recording is 99.8%. At a thickness of 3.75 mm the bandwidth of 660 pm corresponds to an index modulation of 740 ppm.

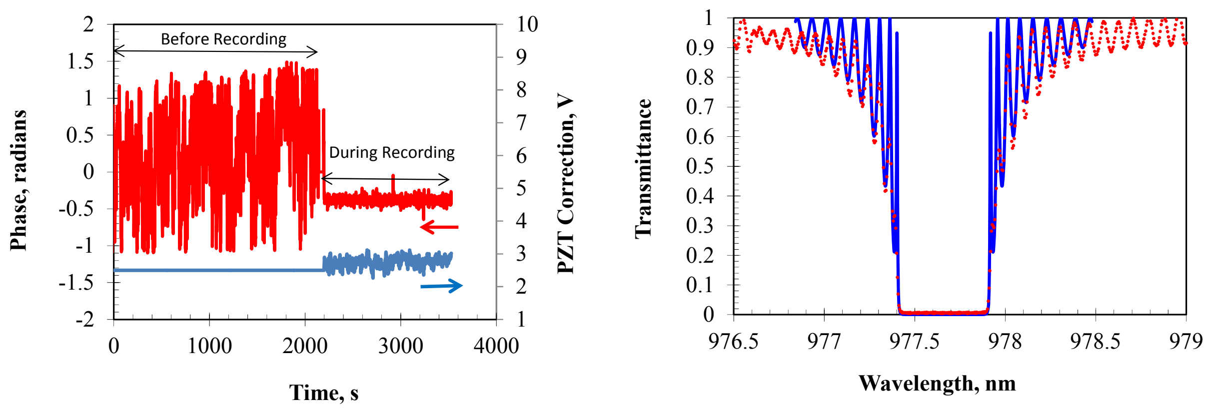
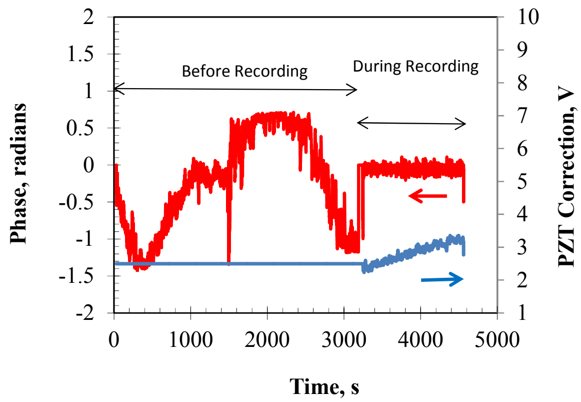


Figure 6. The recording of a stabilized grating. The relative phase of the recording beams (left) shows high frequency noise. The correction applied to the PZT is shown at left in blue. The resulting transmission spectrum (right) of a 3.75 mm thick grating has a bandwidth of 660 pm FWHM.

The grating shown in Fig. 6 did not undergo a long-term drift as was present in the unstabilized case, so a third RBG was recorded where the environmental phase variation (Fig. 7) showed a long term drift similar to that of the grating in Fig. 5. The expected visibility from the measured relative phase during recording is 99.7% and RMSE is 0.0057λ . At a thickness of 3.75 mm the bandwidth of 670 pm corresponds to an index modulation of 750 ppm. This value matches well with that of the grating in Fig 6, confirming proper measurement of relative phase and effective correction.



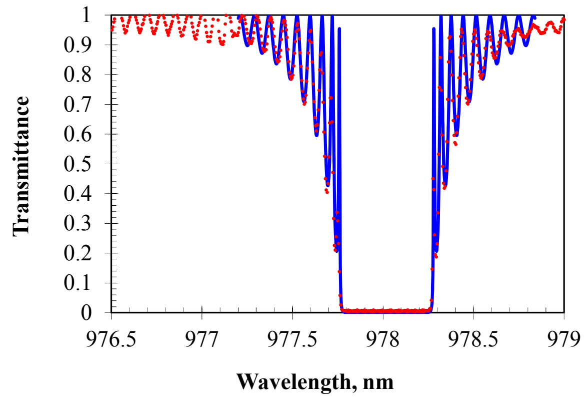


Figure 6. The recording of a stabilized grating. The relative phase of the recording beams (left) shows long term drift. The correction applied to the PZT is shown at left in blue. The resulting transmission spectrum (right) of a 3.75 mm thick grating has a bandwidth of 670 FWHM.

5. CONCLUSIONS

A demonstration of a new method for phase stabilization is shown to be effective in stabilizing the relative phases of a two beam interference pattern. The method can be applied to the recording of VBGs of arbitrary period without the need for specialized components or difficult alignment procedures. Simulations regarding the effect of shifting phase show that RMSE variations must be maintained below 0.05λ to maintain fringe visibility above 95%. The proposed system is shown to produce phase stabilization of both the probe and recording beams well within this tolerance. This phase control setup provides the ability to create repeatable VBGs with maximum refractive index modulation by ensuring fringe visibility of close to 100%. A dramatic increase of nearly two times in the induced refractive index modulation is shown by using phase stabilization during the recording of several gratings.

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