Experimental demonstration of an automatic alignment system for optical interferometers

Euan Morrison, Brian J. Meers. David I. Robertson, and Henry Ward

An automatic alignment system, based on a differential phase-sensing technique described in a companion paper [Appl. Opt. **33, 0000**, (1994)], has been experimentally demonstrated on the 10-m prototype laser interferometric gravitational wave detector in Glasgow. The alignment system developed was used to control the orientations of two mirrors in a 10-m-long suspended Fabry–Perot cavity with respect to the direction defined by the input laser beam. The results of the test and a discussion of the performance of the system are given.

Key words: Alignment, interferometry, Fabry–Perot, gravitational wave detectors.

Introduction

In high-precision interferometers, such as those currently being developed as gravitational wave detectors (see e.g., Refs. 1–3), differential phase modulation is normally applied to permit the relative phase of two interfering beams at the output of the interferometer to be determined. A feedback system is then often used to maintain a null fringe at the output of the interferometer. In a companion paper[4] we demonstrated that in any interferometer locked by use of a differential phase-modulation technique, information about the mismatch in the overlap of the two beams at the output can also be obtained.

A purely angular misalignment of the two beams at the output of the interferometer results in a differential phase gradient across the interference pattern. This phase gradient can be detected with a split photodiode (with the split centered on the interference pattern). We also showed that it is possible to use a further split photodiode to obtain information about any lateral offsets that may be present. We can also extend the technique by using annularly split photodiodes to detect any difference in the radius of curvature of the phase fronts or beam-size mismatches; this was not demonstrated in the experiments discussed here.

When this research was performed, the authors were with the Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, Scotland. B. J. Meers is now deceased.

Received 7 July 1993; revised manuscript received 15 November 1993.

0003-6935/94/225037-04$06.00/0.

The initial tests of such an alignment technique were made earlier by one of us (H. Ward) with a 40-m-long suspended mirror cavity at the California Institute of Technology, but full development of the system and evaluation of its performance were not possible at that time. More recently the technique has been implemented on one of the 10-m optical cavities that forms part of the prototype gravitational wave detector in Glasgow. The cavity is locked with the standard rf reflection locking technique,[5] and in such a situation the two interfering beams may be thought of as the directly reflected light from the input mirror and the light that leaks out of the cavity on resonance. Differential modulation is achieved by phase modulation of the light directed toward the cavity. The component that is directly reflected off the input mirror retains the modulation, whereas the light leaking out of the cavity on resonance has negligible phase modulation, provided the modulation sidebands do not resonate in the cavity. Adjustment of the pointing directions of the suspended mirrors can cause both relative angular and lateral misalignments of these two beams.

Experimental Setup

The 10-m cavity used to demonstrate the automatic alignment system consists of two high-quality dielectric supermirrors suspended as pendulums to give some isolation from seismic noise and situated inside a vacuum system. The mirrors are coated directly onto cylindrical fused-silica masses, 4 in. (10.16 cm) in diameter, 5 in. (12.7 cm) long, and having a mass of ~3 kg. The input mirror has a transmission of 500 ppm in intensity and is plane. The end mirror, which is of maximum reflectivity, has a radius of curvature of 15 m. The cavity is illuminated by laser light from a cw argon-ion laser of 514-nm wavelength. The beam waist of the cavity is situated at the surface of the input mirror and has a radius of ~1 mm. During the tests of the automatic alignment system the cavity was locked in the TEM_{00} mode. The fringe visibility[6] with optimum alignment was quite poor—~30%, limited by excess losses caused by (temporarily) contaminated mirrors. The finesse of the cavity was ~3000.

As illustrated in Fig. 1 the plane/curved nature of the cavity causes tilts and rotations of the curved mirror to couple exclusively to relative lateral offsets of the interfering beams. Misalignments of the plane mirror produce relative beam tilts that appear to originate from a point at the center of the cavity.

Plane-polarized light is phase modulated at 12MHz by use of a Pockels cell and directed toward the cavity through a polarizing beam splitter and a quarter wave plate to form an optical diode. The light beams returning from the cavity are therefore rejected from the polarizing beam splitter and can be detected with one or more photodiodes. Coherent demodulation of the signal from a single photodiode looking at the whole interference pattern yields a signal that is a measure of the offset from the resonance of the cavity. A suitable signal may then be developed to control either the axial position of the mirrors that form the cavity or, as was done during these tests, the frequency of the laser light; this servo system thus locks the cavity on resonance.

Optical Arrangement of the Automatic Alignment System

The optical arrangement of the system and some of the sensing and mixing electronics are shown schematically in Fig. 2. Two quadrant diodes were used to provide alignment information in each of two orthogonal directions. A schematic diagram of the front-end electronics for a single dimension of a quadrant diode is shown in Fig. 3. Each opposite pair of diode segments was resonated in a tuned

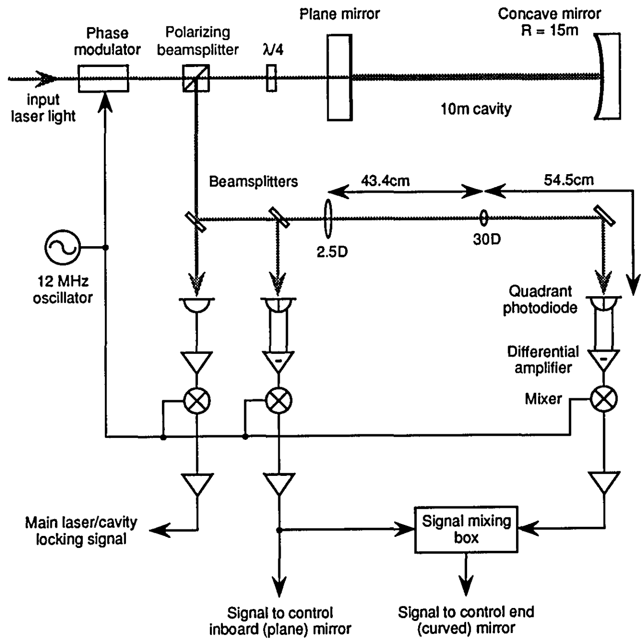

Fig. 2. Schematic layout of a 10-m suspended optical cavity and the main elements of the control system used for autoalignment in one dimension.

circuit to enhance sensitivity at the 12-MHz modulation frequency, with the tuned transformer conveniently providing the required difference signal.

One diode was placed close to the beam waist at the cavity input mirror to sense any angular misalignments of the beams. The resulting signals depended almost exclusively on misalignments of the input mirror, and after suitable filtering these signals were used for feedback control of the orientation of this mirror.

As discussed in our companion paper,[4] lateral offsets could be sensed by a second photodiode either positioned a great distance from the beam waist or

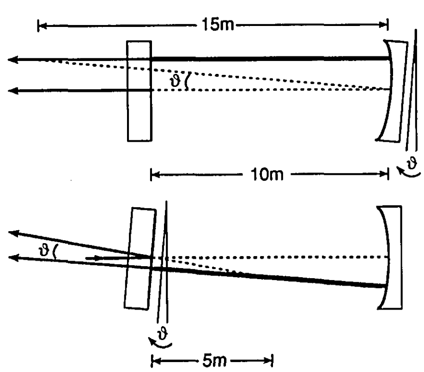

Fig. 1. Effects of misalignment of the two mirrors in the plane/curved cavity used for the tests. The directly reflected and cavity leakage beams are indicated schematically by the arrowed lines. (The incident beam in each case is propagating horizontally and strikes the plane mirror at its midpoint.) Note that the path followed by the superposition of the two components depends on their relative magnitudes.

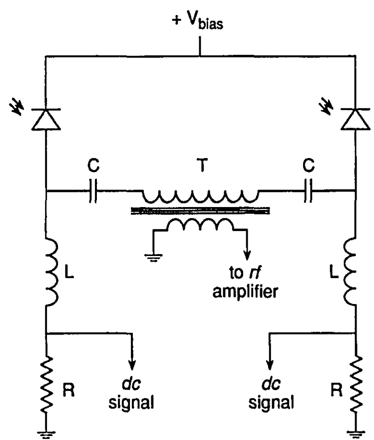

Fig. 3. Schematic diagram showing a tuned photodiode front end for one dimension. Voltages dropped across resistors R permit monitoring of the dc photocurrents. Components L and C ensure that the rf photocurrents are directed to the transformer T, which is tuned with the photodiode capacity to resonate at the phase modulation frequency.

alternatively placed close to the focal point of a suitable lens. However, with the cavity used in these tests neither solution was convenient as a method of introducing a phase shift between the first-order and fundamental modes that was large enough to give efficient signal detection. With no lens the photodiode would have to be placed several meters away from the beam waist. If a single lens were to be used, it would have to have a reasonably short focal length (~ 1 m) to keep the physical size of the optical system manageable. Even for a focal length of 1 m, the waist formed by the lens would be ~ 170 μm for an input waist of 1 mm. Typically the gap between segments of the quadrant diodes is ~ 200 μm; the spot size would thus be too small for satisfactory use. Even if the loss of light in the gaps were to be tolerated, a servo system would almost certainly have to be used to keep the interference spot centered on the photodiode.

In practice the multiple-lens system shown in Fig. 2 was used. It was relatively compact in size (~ 1 m in length) and gave a sufficient phase shift between the first-order and fundamental modes to allow detection of any misalignment of the curved mirror, while maintaining a beam size of ~ 1 mm on the second quadrant photodiode.

The signal detected with the second quadrant photodiode was also sensitive to misalignment of the plane mirror in the cavity. As discussed in our theoretical treatment,[4] in principle we can null out completely the dependence of this signal on misalignments of the plane mirror by carefully choosing the powers and positions of the lenses in front of the second quadrant photodiode. In practice, however, it is more convenient simply to ensure that the signal detected with the second quadrant photodiode has some reasonable dependence on the misalignment of the curved mirror and then to subtract out electronically (with the signals from the first quadrant photodiode) any component caused by misalignment of the plane mirror. We set up the system by dithering the alignment of the input mirror at a few hertz and observing the resulting signal in the output of the mixing circuit. This component could then be nulled out by suitable adjustment of the mixing ratio, resulting in a signal that was proportional solely to misalignment of the curved mirror.

Coil/magnet actuators were used to control the orientation of the suspended mirrors. Each mirror is suspended by two loops of wire from a suspended control block. By driving current through coils, we applied forces to magnets attached to the control blocks, thereby allowing the tilt and rotation of the mirrors to be adjusted. These actuators are also used together with locally acting optical sensors to damp the high-Q pendulum resonances, preventing excessive motion of the mirrors at these frequencies. Each automatic alignment servo was designed with suitable electronic filtering to give a bandwidth of ~ 10 Hz and an open loop gain of ~ 20 dB below the pendulum resonances (~ 1 Hz).

Performance

The performance of the system could be judged by observing the visibility of the interference fringe viewed in reflection when the laser was stabilized to be on resonance with the cavity. Any misalignment of the cavity axis with respect to the input beam direction results in coupling of the input light into higher-order modes. The amount of light in the fundamental mode is therefore decreased, resulting in a decrease in the observed visibility.

As a test of the alignment system, each mirror was deliberately misaligned by a small amount in each of its two degrees of freedom. The servo systems were then switched on one at a time resulting in the stepwise improvement in the visibility shown in Fig. 4.

The visibility was improved from $\sim 20\%$ to the optimum value of 30%, equal to the best that one could obtain by manually steering the mirrors with electronic offsets applied to the locally acting orientation servo controls.

It is also interesting to note that the fluctuations in the visibility are enhanced when the cavity is misaligned. This is due to the static offsets in the alignment of the cavity mirrors increasing the coupling of large low-frequency motions of the suspended mirrors into the light intensity in the interference pattern.

The error points of the servos were also measured and calibrated to give estimates of the angular fluctuations as viewed by the automatic alignment systems. The error point of the servo used to control the tilt of the curved mirror is shown in Fig. 5.

With the servo switched off (upper trace), it can be seen that the low-frequency angular fluctuations correspond to a level of a few times 10^{-6} rad$/\sqrt{\text{Hz}}$ and fall off into the background measurement noise level at ~ 10 Hz. This spectrum was similar for all the servo systems used to control the orientation of the two mirrors in the cavity. The low-frequency fluctuations are probably due to seismic noise that propa-

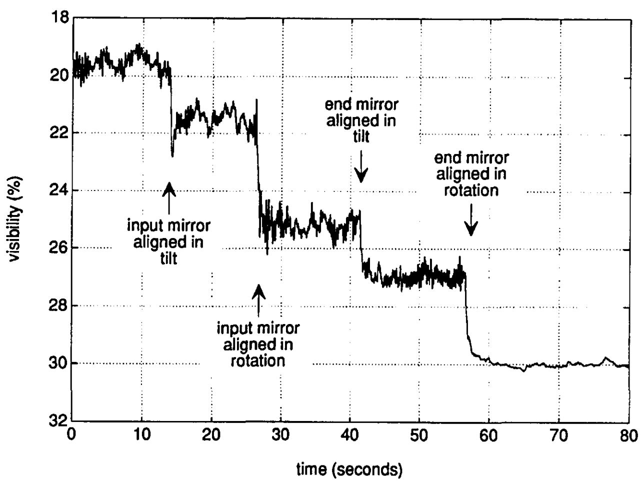

Fig. 4. Effect of the automatic alignment system on the fringe visibility of the 10-m cavity.

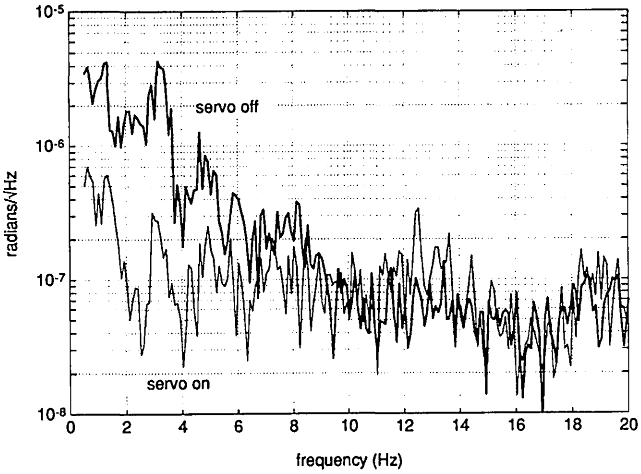

Fig. 5. Angular fluctuations as viewed by the sensing system used to control the tilt of the curved mirror in the 10-m cavity.

gates through the suspension system with little attenuation at these frequencies. The background noise is not shot noise but excess intensity noise on the light at the rf modulation frequency caused by a lack of optical isolation in the system. The shot noise level was $\sim 10^{-10}$ rad/$\sqrt{\text{Hz}}$.

Switching on the alignment system (lower trace) results in a reduction of the angular fluctuations at low frequencies by at least 20 dB. This reduction was as expected, given the design of the servo.

Problems and Limitations

With systems operating at low frequencies the main problems to be expected are in stability of operation. Good dc stability in the feedback electronics is essential. While offset voltages that can arise at the inputs to the various amplifiers used can in principle be nulled out when the system is set up initially, any drifting of these voltages will cause misalignment of the cavity mirrors.

Similar problems can be caused by rf pickup in the electronics before the mixers that can also produce dc offsets in the servos. Although one can also deal with these effects by nulling out the offsets using suitable correction voltages, the amount of pickup in the front- end electronics can be surprisingly variable unless good shielding is employed.

The main optical limitation to the sensitivity of the technique was the excess light noise caused by a lack of optical isolation in the system, which set a limit of $\sim 10^{-7}$ rad/$\sqrt{\text{Hz}}$ on the angular stability that could be achieved at low frequencies. It is expected that additional optical isolation should significantly reduce this noise source.

Summary and Conclusions

A differential phase-sensing technique has been successfully applied to align the mirrors in one of the 10-m-long suspended optical cavities in the Glasgow prototype gravitational wave detector. In this test it was possible to achieve a loop gain for each degree of freedom of more than 20 dB at frequencies below a few hertz.

We thank our colleagues in the Gravitational Waves Research Group for their interest in this research, which was supported by the Science Engineering Research Council the University of Glasgow.

References and Notes

1. R. E. Vogt, A. Abramovici, W. Althouse, R. Drever, Y. Gürsel, S. Kawamura, F. Raab, D. Shoemaker, L. Sievers, R. Spero, K. Thorne, R. Weiss, S. Whitcomb, and M. Zucker, "The U.S. LIGO project," in *Proceedings of the Sixth Marcell Grossmann Meeting on General Relativity,* H. Sato and T. Nakamura, eds. (World Scientific, Singapore, 1992), pp. 244–266.
2. A. Giazotto, A. Brillet, C. Bradaschia, R. Del Fabbro, A. Di Virgilio, H. Kautzky, V. Montelatici, D. Passuello, F. Barone, L. Di Fiore, L. Milano, G. Russo, S. Solimeno, M. Capozzi, M. Longo, M. Lops, I. Pinto, G. Rotoli, F. Fuligni, V. Iafolla, G. Natale, O. Cregut, P. Hello, C. N. Man, P. T. Manh, A. Marraud, D. Shoemaker, J-Y. Vinet, J. M. Aguirregabiria, H. Bel, J-P. Duruisseau, G. Le Denmat, P. Tourrenc, T. Damour, S. Bonazzola, J. A. Marck, Y. Gourghoulon, and L. E. Holloway, *The VIRGO Project,* (INFN, Pisa, Italy, 1989).
3. K. Danzmann, J. Chen, P. G. Nelson, T. M. Niebauer, A. Rüdiger, R. Schilling, L. Schnupp, K. A. Strain, H. Walther, W. Winkler, J. Hough, A. M. Campbell, C. A. Cantley, J. E. Logan, B. J. Meers, E. Morrison, D. I. Robertson, N. A. Robertson, S. Rowan, K. D. Skeldon, P. J. Veitch, H. Ward, H. Welling, P. Aufmuth, I. Kröpke, D. Ristau, J. E. Hall, J. R. J. Bennet, I. F. Corbett, B. W. H. Edwards, R. J. Elsey, R. J. S. Greenhalgh, B. F. Schutz, D. Nicholson, R. J. Shuttleworth, J. Ehlers, P. Kafka, G. Schäfer, H. Braun, and V. Kose, "The GEO project: a long baseline laser interferometer for the detection of gravitational waves," in *Relativistic Gravity Research with Emphasis on Experiments and Observations,* Vol. 410 of Lecture Notes in Physics, J. Ehlers and G. Schäfer, eds. (Springer-Verlag, Berlin, 1992), pp. 184–209.
4. E. Morrison, B. J. Meers, D. I. Robertson, and H. Ward, "Automatic alignment of optical interferometers," Appl. Opt. **33,** (1994).
5. R. W. P. Drever, J. L. Hall, F. W. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, "Laser phase and frequency stabilization using an optical resonator," Appl. Phys. B **31,** 97–105 (1983).
6. We calculate the fringe visibility V from the intensity of the light reflected from the cavity in the unlocked state I_0 and the reflected intensity with the cavity locked I_l using the equation

$$V = \frac{I_0 - I_l}{I_0}.$$