Squeeze and you shall measure: Squeezed coherent states shown to be optimal for gravitational wave

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An aerial view (3) of LIGO Hanford Observatory (LHO)

Extremely precise measurements of distances are key in all techniques used to detect gravitational waves. To increase this precision, physicists have started using quantum effects linked with photons. A paper published in *Physical Review A* by Polish and German physicists shows that it is not necessary to use quantum light states more refined than the squeezed coherent states available currently.

For close to a century, gravitational waves have been an unconfirmed prediction of the theory of general relativity. Vibrations of spacetime are likely to be so subtle that they cannot be detected by even state-of-the-art detectors such as the laser interferometers LIGO and GEO 600. Recently, scientists at the Faculty of Physics at the University of Warsaw demonstrated that the sensitivity of the detectors can be improved using quantum effects linked to light. Now the Warsaw physicists and researchers from the University of Hanover have shown that experimentally available squeezed states are optimal for using quantum properties to improve the precision of measurements.

"Our finding is applicable to all quantum metrology. However, the practical applications are especially relevant to physicists searching for gravitational waves, since they are trying to make the most extreme measurements of distances," notes Dr Rafał Demkowicz-Dobrzański from the University of Warsaw.

General relativity predicts that gravitational waves may be emitted by binary star systems comprising extremely dense bodies such as neutron stars or black holes. However, even for such exotic objects, the ripples caused in spacetime are extremely subtle. A gravitational wave passing through Earth should marginally affect sizes of objects, therefore it could be detected by conducting extremely precise measurements of distances. Sufficient precision can only be achieved using interferometers – devices that use laser beams and the phenomenon of wave interference.

A typical gravitational wave detector is an interferometer with two perpendicular arms. A beam of laser light travels along each arm, and the two beams interfere with one another to create a distinctive pattern of interference bands. If a gravitational wave passing through the device changes the length of one of the arms slightly with respect to the other, the peaks and troughs of the light waves from the two beams would shift against one another, altering the layout of the bands.

The American-built LIGO, the most sensitive detector of gravitational waves to date, is a system of three interferometers with arms of lengths between 2 and 4 km. In spite of such massive sizes of the arms, even the most powerful gravitational waves change their length by at most a billionth of a billionth of a meter (0.000,000,000,000,000,001 m). LIGO operates on the boundary of detecting gravitational waves; however, physicists are still unable to detect them, since the signals that reveal the passing of gravitational waves are lost in background noise. It is possible to improve the accuracy of measurements by using quantum properties of photons in laser beams.

Ordinary light sources emit chaotic light with photons travelling at different wavelengths and in different directions. In this case, the behavior of photons can be compared to the motion of people in a city square – each one is moving wherever they want at their own pace. Laser light is far more ordered: the wavelength of each photon is the same, vibrates in the same phase, and runs in approximately the same direction as the others. Such light more closely resembles a column of soldiers marching in step in a single direction.

However, the analogy between laser light and a marching column of soldiers is somewhat misleading. Each photon in a laser beam behaves as though it was on its own – it doesn't "notice" any of the others. It is as though someone – either a deranged corporal or a laser emitter – has formed a column of expertly trained soldier-photons and ordered them to march straight ahead, without realizing that they are all completely deaf and blind. Each individual continues to press ahead even though the mad corporal is left far behind.

"In a real marching column, individual soldiers are well aware of their colleagues, and keep adjusting their motion to match that of their neighboring soldiers. They may not even be doing it consciously, but they certainly do it, since it is information on the activities of their fellow marchers that allows them to keep in formation. In order for photons to behave the same way, we need to use quantum effects, such as quantum entanglement," explains Dr Demkowicz-Dobrzanski.

In 2011, in order to improve the sensitivity of measurements, scientists working at the European interferometer GEO 600 near Hanover used laser light placed in a specially prepared quantum state known as a squeezed vacuum. Electrical and magnetic fields can exist in a physical vacuum, although their mean values are equal to zero. In quantum optics, it is impossible to conduct precise concurrent measurements of electrical and magnetic fields of light waves. The values are subject to the uncertainty principle: the better we understand one, the less we know the other. The squeezed vacuum state also has zero mean values of electrical and magnetic fields; however, it is constructed in such a way that we are able to conduct precise measurements of the value of one of the fields (at the cost of the other). Using quantum correlated photons yielded an approx. 30% increase in the GEO 600 interferometer's sensitivity to shifts in the mirrors at the end of its arms.

Such an achievement, of course, only whets scientists' appetite for more: might using increasingly sophisticated quantum states of light, with numerous photons, pave the way for further improvements in sensitivity? Physicists from the University of Warsaw have been able to answer this question by analyzing it theoretically. A key element of the analysis was the fact that approx. 30% of photons are lost in gravitational wave detectors. In an ordinary laser beam, when some of the photons are lost, the beam loses intensity, but its other properties remain unchanged. In quantum states involving high numbers of photons, the loss of a single one means that quantum correlations between the others are destroyed.

Making complex quantum states sufficiently resilient to conduct more precise measurements becomes extremely difficult in this situation.

"Everything suggests that experimental physicists have reached an optimal level of using quantum states to increase the sensitivity of interferometers using quantum phenomena. Even if we try to use more subtle quantum states of light, we cannot squeeze any better results from the equipment currently at our disposal," concludes Dr Demkowicz-Dobrzański.

Results obtained by the team of physicists from the Universities of Warsaw and Hanover have significant practical applications. They mean that it is not necessary to create more subtle quantum states than squeezed light states, and improved sensitivity of gravitational wave detectors will be made possible mainly thanks to changes to the geometry of the course of light beams through interferometers, reducing losses, or by significantly extending the length of the arms. In the latter case, the natural direction of development will be constructing detectors in space.

Provided by University of Warsaw