Dispersion cancelled low coherence interferometry

Prabakar Puvanathasan\textsuperscript{1,2}, Kevin J. Resch\textsuperscript{1,3}, Jeff S. Lundeen\textsuperscript{4}, Morgan W. Mitchell\textsuperscript{5} and Kostadinka Bizheva\textsuperscript{1}

1. Dept. of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada
2. Dept. of Systems Design Engineering, University of Waterloo, Waterloo, Ontario, Canada
3. Institute of Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada
4. Clarendon Laboratory, University of Oxford, Parks Rd, Oxford, United Kingdom
5. ICFO – Institut de Ciencies Fotoniques, Mediterranean Technology Park, Castelldefels (Barcelona), Spain

Phone: +1 519 888 4567 x 35665; Fax: +1 519 746 8115; E-mail: kbizheva@sciborg.uwaterloo.ca

Abstract: Even-order dispersion cancellation, an effect previously identified with frequency-entangled photons, is demonstrated experimentally for the first time with a linear, classical interferometer. A combination of a broad bandwidth laser and a high resolution spectrometer was used to measure the intensity correlations between anti-correlated optical frequencies. Only 14\% broadening of the correlation signal is observed when significant material dispersion, enough to broaden the regular interferogram by 4250\%, is introduced into one arm of the interferometer.

Keywords: Optical coherence tomography, Fourier domain OCT, biomedical optics, medical imaging, dispersion cancellation, interferometry

Biography: Prabakar Puvanathasan has obtained a B.Sc. degree (Systems Design Engineering) from University of Waterloo, Canada in 2006. He is currently working towards MSc degree in Physics with Dr. Kostadinka Bizheva at University of Waterloo, Canada. His interests focus on signal and image processing and pattern recognition analysis as applied to Optical Coherence Tomography for image enhancement.
Dispersion cancelled low coherence interferometry

Prabakar Puvanathasan$^{1,2}$, Kevin J. Resch$^{1,3}$, Jeff S. Lundeen$^4$, Morgan W. Mitchell$^5$ and Kostadinka Bizheva$^1$

1. Dept. of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada
2. Dept. of Systems Design Engineering, University of Waterloo, Waterloo, Ontario, Canada
3. Institute of Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada
4. Clarendon Laboratory, University of Oxford, Parks Rd, Oxford, United Kingdom
5. ICFO – Institut de Ciencies Fotoniques, Mediterranean Technology Park, Castelldefels (Barcelona), Spain

Phone: +1 519 888 4567 x 35665; Fax: +1 519 746 8115; E-mail: kbizheva@sciborg.uwaterloo.ca

ABSTRACT

Even-order dispersion cancellation, an effect previously identified with frequency-entangled photons, is demonstrated experimentally for the first time with a linear, classical interferometer. A combination of a broad bandwidth laser and a high resolution spectrometer was used to measure the intensity correlations between anti-correlated optical frequencies. Only 14% broadening of the correlation signal is observed when significant material dispersion, enough to broaden the regular interferogram by 4250%, is introduced into one arm of the interferometer.

INTRODUCTION

Low-coherence, or white-light, interferometry is an important technique for precise measurements of material properties, such as optical path length or dispersion. In this technique, time resolution is limited by the coherence length of the light; shorter coherence lengths, from broader band sources, can give better resolution. Unfortunately, the resulting interferograms become increasingly sensitive to dispersive broadening as the bandwidth is increased. This creates an effective limit to resolution, beyond which increasing the bandwidth further does provide narrower interference features, without a method for managing or removing effects of dispersion.

In 1992, an interferometer based on frequency-entangled photon pairs was demonstrated to be insensitive to even-order dispersion while maintaining its sensitivity to optical path delays [1]. More recently, this interferometer was proposed as the basis for quantum-optical coherence tomography [2] in the hopes of marrying dispersion-cancellation with the medical imaging technique called optical coherence tomography [3].

In this work, we show that dispersion cancellation can be achieved using only a classical light source, linear optics, and frequency-correlated detection. We review quantum dispersion cancellation and use its essentials to design an analogous classical system.

METHODS

Dispersion cancellation is straightforward in quantum interferometry, but the methods proposed so far in classical interferometry are not [4]. Our approach in this work is to use the intuition derived from quantum technologies to achieve dispersion cancellation in a straightforward classical interferometer. Dispersion cancellation in quantum interferometry required frequency-anticorrelated entangled photons in a fourth order interferometer (i.e. coincidence signal). Entanglement is not a classical concept, however classical physics does allow frequency correlations. Consider the interferometer shown in Figure 1a) – a standard Mach-Zehnder configuration with a broadband light source. In each output is a spectrometer which measures the spectral interference fringe. A dispersive sample can be placed in one of the arms. A mirror is moved in the other arm and a function of the spectral data, $S$, is calculated at each delay position, $\Delta$.

Instead of measuring the total intensity, as is done in a standard white-light interferometer, we use the spectral data to extract the following function for each delay position:

$$S(\Delta) = \int d\delta \omega, I_1(\omega_{\Delta} + \delta \omega) I_2(\omega_{\Delta} - \delta \omega)$$

where $I_1$ and $I_2$ are the intensities measured at the two different spectrometers for a frequency $\omega_{\Delta} \pm \delta \omega$. Notice that this function is a fourth-order signal, since it is the product of two intensities, and the intensities involved are from...
perfectly anti-correlated frequencies (i.e. the frequencies sum to a constant value). We assume that the sample introduces a purely dispersive phase shift \( \phi(\omega) = k(\omega)L \), where \( L \) is the length of the material. We expand the wavevector about a central frequency \( \omega_0 \),

\[
k(\omega_0 + \delta\omega) = k_0 + \frac{dk}{d\omega} \delta\omega + \frac{1}{2} \frac{d^2k}{d\omega^2} \delta\omega^2 + ... .
\]

Assuming that each individual frequency has perfect interference visibility and that the spectrum is symmetric about the central frequency \( \omega_0 \), we expect the signal function:

\[
S = \frac{1}{2} \int d\delta\omega \left[ 1 - \frac{1}{2} \cos \left( \frac{2\delta\omega L}{c} + 2L \frac{dk}{d\omega} \delta\omega + O\left( \frac{d^2k}{d\omega^2} \right) \right) \right] ^2.
\]

where \( \Delta \) is the delay position and \( c \) is the speed of light. The first term depends on the relatively slow \( \delta\omega \) and is insensitive to all even orders of dispersion including the dominant second-order term. That term does, however, retains its sensitivity to group delays. The second term, while being sensitive to dispersion, oscillates at the much faster \( \omega_0 \). This creates a separation of timescales which allows us to extract the slow, dispersion-cancelled signal from a rapidly oscillating background.

The experimental setup is shown in Fig. 1b. A compact, fiber-pigtailed, femtosecond laser (Femtolasers Inc., centre wavelength 792nm, bandwidth FWHM 154nm, average power 60mW) was coupled to a fiber-based Michelson interferometer. A pair of BK7 prisms mounted on miniature translation stages in the reference arm of the system were used to precisely compensate material dispersion mismatch between the two arms of the interferometer. The focusing lens and the mirror in the reference arm of the system were mounted on a computer-controlled translation stage for variable optical delay. The interference pattern generated by light reflected from the sample and reference mirrors was detected with a high-resolution (0.09nm) and high-speed (20 kHz readout rate) spectrometer and recorded by a computer. To demonstrate dispersion cancellation with the classical interferometer, measurements were made both in a dispersion-balanced system and when flat, uncoated, BK7 optical windows of thickness 4.690\pm0.005mm, 5.940\pm0.005mm, and 6.170\pm0.005mm (and several possible combinations) were introduced into the sample arm. For each measurement, the reference mirror was translated in steps of 0.1\mu m and the spectral interference fringes were acquired with a readout time of 60 \mu s per step. The calculation of the signal function, \( S \), was performed in the following way. One spectrometer reading was taken for each motor position to provide us with \( I_0(\omega, \Delta) \). The wavelength scale was converted to frequency and nonlinear interpolation was used to extract intensities at evenly spaced intervals. We obtained \( I(\omega) \) by measuring the intensity from the sample and reference arm separately and doubling their sum. Energy conservation, \( I(\omega) = I_0(\omega, \Delta) + I_0(\omega, \Delta) \), was applied to extract \( I(\omega) \) without the necessity for a second spectrometer. To satisfy the assumption in our theory that \( I(\omega) \approx I(2\omega_0 - \omega) \), \( I(\omega) \) and \( I_0(\omega) \) was multiplied by a mirror version of \( I(\omega) \) with respect to the centre frequency \( \omega_0 \). The integral \( S \) was approximated by a discrete sum over 4096 equally spaced energies.

RESULTS AND DISCUSSION

In Figure 2, we show some of the data, \( S(\Delta) \), from our experiment which have been subjected to a low-pass filter to remove the rapidly oscillating component. Figure 2a) was taken with no additional dispersive material in the setup,
and the dispersion from mismatched fibre lengths balanced. The corresponding standard white-light fringe pattern
(not shown) had FHWM of 2µm whereas this signal, \( S(\Delta) \), has FHWM of 1.6µm. Figure 2b) was taken with an
additional 16.8mm of glass in one of the arms of the interferometer through which the light passed through twice.
This was sufficient dispersion to broaden the standard white-light fringe pattern (not shown) by 4250%, while the
signal, \( S(\Delta) \), is broadened by only 14%.

![Experimental Data. Measured S(\Delta) with a) no additional dispersive material and b) 16.8mm of BK7 glass. The signal is broadened by only about 14% while the standard intensity interference pattern (not shown) is broadened by 4250%.](image)

Our technique shows that dispersion cancellation can be achieved in a completely classical interferometer without
the need for next generation technologies or additional assumptions about the dispersive nature of the sample of
interest. Our results clarify the role of entanglement in quantum interferometry and simplify a potentially powerful
tool for precision interferometric measurements and imaging.

**CONCLUSION**

We have theoretically derived and experimentally demonstrated a method for cancelling even order dispersion in
classical low-coherence interferometry. Dispersion cancellation is not an uniquely quantum effect, since it can also
be observed in completely classical systems. However, the interference visibility in our classical analogue is only
half that achievable in quantum interferometers [6, 8]. Our approach dramatically reduces experimental barriers for
dispersion cancellation in low-coherence interferometry and optical coherence tomography.

**ACKNOWLEDGEMENTS**

The authors wish to thank Aephraim Steinberg for valuable discussions, Gregor Weihs for loaning us equipment, H.
Van der Heide and J. Szubra, Uwaterloo Science shop for their assistance with electronic and mechanical designs.
We are grateful for the inkind support provided by O. Pawluczyc and R. Pawluczyc from P&P Optica. We also
would like to acknowledge financial support provided by NSERC, ORDCF and University of Waterloo.

**REFERENCES**