Modulation techniques for length sensing and control of advanced optical topologies

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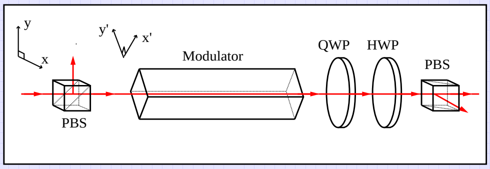
Multi-cavity optical topologies

The interaction between optical cavities with high circulating light power will be a key feature of future gravitational wave detectors. Controlling the resonance condition of multiple coupled cavities will require the use of complex and flexible optical modulation schemes. To this end we have developed a novel technique for generating length sensing sidebands using a simple optical alteration from a conventional intensity modulation set-up.

Novel modulation configuration



Modulation configuration – uses a combination of polarising beam splitters, and quarter and half wave-plates. Output sideband structure is adjusted by rotating the wave-plates.

An intensity modulator can be created by placing an electro-optic modulator (EOM) and a quarter wave-plate (QWP) between crossed polarisers (PBS's).

- Set QWP to give circular polarisation
- Apply sinusoid to EOM – get intensity modulation

Addition of a half wave-plate (HWP) into this system

- Adjust polarisations and relative amplitude and phase of carrier and sidebands
- Get amplitude and phase modulation (AM and PM)

Modulation and polarisation

The conventional interpretation of modulation is to use the generic first order electric field approximation

$$E_{out} = E_0 e^{i\omega_0 t}\left(M_C + iM_1 e^{i\omega_m t} + iM_2 e^{-i\omega_m t}\right)$$

where M_C, M_1 and M_2 are the complex electric field amplitudes of the carrier, upper and lower sidebands (USB, LSB) with modulation frequency ω_m.

To calculate the modulator output fields, a polarisation approach is adopted based on Jones matrices. The EOM is treated as a variable wave-plate with the form

$$\text{Carrier}: V_C = J_0\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$\text{USBand}: V_U = J_1\begin{bmatrix} \exp(-i\alpha) & 0 \\ 0 & \exp(i\alpha) \end{bmatrix},$$

$$\text{LSBand}: V_L = J_1\begin{bmatrix} \exp(i\alpha) & 0 \\ 0 & \exp(-i\alpha) \end{bmatrix}.$$

where J_0 and J_1 are Bessel functions of the first kind, and α is the phase change associated with the magnitude of the modulating voltage. Note that, when this wave-plate is rotated, the USB and LSB will be right and left elliptically polarised respectively.

Separating frequency components

Fundamentally, polarising optics work by shifting the phase of light in one axis relative to another. Tracing each frequency component through the configuration

- Both carrier and sideband polarisation changes
- Carrier phase changes relative to initial phase
- ω_m phases don't change relative to initial phase

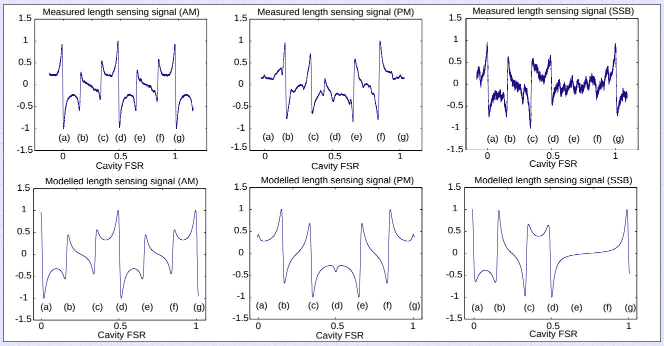
Interpreting in terms of complex field magnitudes

- M_C can vary in both amplitude and phase
- M_1 and M_2 can only vary in amplitude.

Rotation of the wave-plates thus allows generation of combinations of AM and PM and, because the USB and LSB have different polarisation states, unbalanced and single sideband modulation (SSB).

Experimental verification

The output fields from the new modulation set-up were modelled, modulated using a second PM and used as input to a model of the power recycling cavity (PRC) of the Glasgow prototype interferometer.



Comparison of measured and modelled length sensing signals for a full free spectral range (FSR) sweep of the PRC.

Comparing the simulated predictions to the measured data shows excellent agreement.

Length sensing and control

We have implemented both AM and SSB as length sensing signals for a suspended coupled-cavity system. Both schemes provided stable, decoupled control signals over several hours in a stable temperature environment. For longer-term operation it is expected that electronic feedback would be required to maintain stability.

We are currently using this modulation set-up in a table-top Mach Zehnder system to validate optical readout methods for GEO600.

The modulation set-up is an optically simple, and versatile module capable of generating multiple modulation states for the purposes of optical length sensing in advanced interferometric devices.

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