Cavity Resonance Frequency Drift and Methods of Stabilization in the Newport SuperCavity™ High Finesse Optical Spectrum Analyzer

Newport

Introduction

All interferometric spectrum analyzers have sources of drift. The greater the resolving power of the interferometer, the more sensitive it becomes to a number of operating and environmental parameters which cause changes in the cavity resonance frequency. When considering sources of drift that are of concern to the user, those involving the thermal and electrical properties of the cavity are of primary importance and therefore, most worthy of analysis.

Obviously, proper design can minimize the effects of cavity resonance drift while still providing a versatile high resolution instrument. Such is the case with Newport's SuperCavity Optical Spectrum Analyzer, a very high resolution, non-confocal, spherical mirror Fabry-Perot interferometer. One family of the SuperCavity Instrument Line exhibits a finesse value at the center wavelength of the bandpass typically >40,000.

As with many modern Fabry-Perot interferometers, the Newport SuperCavity utilizes two mirrors of identical radii-of-curvature mounted on the ends of a piezo-ceramic tube whose properties are fairly well characterized. However, for cavities that exhibit very high finesse like SuperCavity, drift of the cavity resonance frequency, and therefore, the output signal, may become a problem when special care in set-up and environmental isolation is not followed. To identify various sources of drift and to quantify the magnitude of the cavity resonance drift introduced by these sources, it is perhaps beneficial to review terms such as "Free Spectral Range", "finesse", and "resolution".

Free Spectral Range

Interferometry is based on the interference of monochromatic (or quasi-monochromatic) light waves. The condition for constructive interference of the lowest order mode wavefront in an optical cavity with mirrors of long radii is

$$2n\ell = m\lambda \tag{1}$$

where:
- n = index of refraction of the medium
- ℓ = spacing between the interferometer mirrors
- m = spectral order of the interference
- λ = wavelength of incoming light

Each spectral order encompasses a range of frequencies (or wavelengths) which make up the mode structure of the cavity – i.e. mode families that repeat in every spectral order. Free Spectral Range (FSR) is defined as that range of frequencies which span one spectral order, as pictured in Figure 1. The Free Spectral Range that corresponds to the separation in frequency space of each order for a Fabry-Perot type of interferometer is

$$FSR_{\upsilon} = \frac{c}{2\ell} \tag{2}$$

where:
- c = the velocity of light
- ℓ = the separation distance of the mirrors

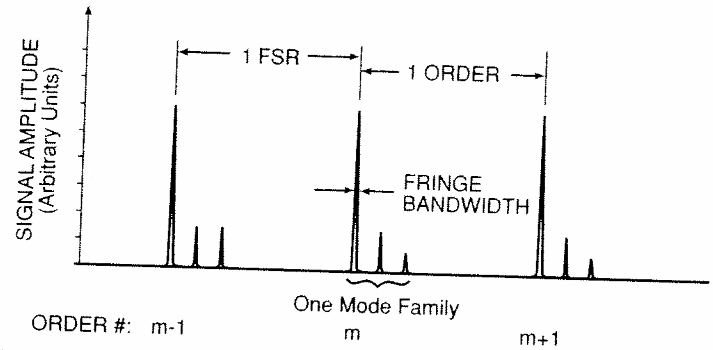

Fig. 1. The relationship of Free Spectral Range and resolution for a non-confocal cavity.

Using equation (2) with, for example, λ = 800 nm, and ℓ = 25.4 mm (nominally a 1" mirror spacing as in the SR-100 Series SuperCavity), then the Free Spectral Range in frequency space is

$$FSR_{\upsilon} = \frac{c}{2\ell} = 6\,GHz \tag{2a}$$

With ℓ = 20 microns (as in the SR-200 Series) and using the same nominal wavelength, then

$$FSR_{\upsilon} = \frac{c}{2\ell} = 7600\,GHz \tag{2b}$$

Although the FSR value calculated in (2) above is more convenient because it is independent of both wavelength and frequency, Free Spectral Range as a function of wavelength, λ, may also be used since a change in the cavity length of $\lambda/2$ also represents a change of one order ($\Delta m = 1$).

Using the relation

$$\frac{d\upsilon}{\upsilon} = \frac{d\lambda}{\lambda} \tag{3}$$

derived from the fundamental relation between wavelength and frequency

$$\lambda\upsilon = c \tag{3a}$$

then, in wavelength space

$$FSR_{\lambda} = \frac{\lambda^2}{c} FSR_{\upsilon} \tag{4}$$

or, using (2),

$$FSR_{\lambda} = \frac{\lambda^2}{2\ell}. \tag{4a}$$

From equation (4a), and using the values of λ = 800 nm and ℓ = 25.4 mm as in (2a) above, then the Free Spectral Range in wavelength is

$$FSR_{\lambda} = \frac{(8\times10^{2}nm)^2}{2(25.4\times10^{6}nm)} = 1.26\times10^{-2}nm \tag{5}$$

With ℓ = 20 microns and using the same nominal wavelength, then

$$FSR_{\lambda} = \frac{(8\times10^{2}nm)^2}{2(20\times10^{3}nm)} = 16nm \tag{5a}$$

With the present voltage output of the SR-DHT Controller (76 Volts) and a 0.030" thick PZT tube ($d_{31} = -250 \times 10^{-12} V^{-1} m$), then the extension available from the tube is from (17) above

$$d\ell = d_{31} \times V \times \left(\frac{1}{t}\right) = -250 \times 10^{-12} V^{-1} m \times 76 V \times \left(\frac{1"}{.030"}\right) \qquad (18)$$

or, after calculations, and because of the method used by the controller to drive the PZT tube doubles the applied voltage value obtained from (18), then

$$d\ell = 1.26 \times 10^{-6}\ m \qquad (19)$$

At a wavelength of 800 nm where a shift of one order is $\lambda/2$, or 400 nm, then $d\ell$ calculated in (19) represents

$$d\ell = \left(1.65 \times 10^{-6} m\right) \times \left(\frac{1\ \text{order}}{400\text{nm}}\right) = 3.2\ \text{orders} \qquad (20)$$

From the results of (17), where a 20 fringe movement (5×10^{-4} order) causes a 1 fringe FWHM creep, then the voltage necessary to produce such a creep is

$$dV = \left(5 \times 10^{-4}\ \text{order}\right) \times \left(\frac{76V}{3.2\ \text{orders}}\right) = 11.9\text{mV}. \qquad (21)$$

This voltage value is on the order of the resolution of the fine centering control of the SR-DHT Controller, so it is possible to introduce considerable voltage creep with any major adjustments of the centering controls. When the necessity to make large voltage changes using the controller becomes apparent, the user should overshoot the desired change by about 5% - 10% and then backtrack slowly to the correct point to minimize the voltage creep.

Electronic Tracking Methods of Signal Stabilization

For cavities with relatively low finesse, electronically tracking a predetermined signal peak is a possible alternative to active thermal control. This method of artificial stabilization, unfortunately, severely limits or totally prevents measurement of any of the frequency and/or mode drift characteristics of the source being analyzed, and becomes increasingly more difficult as the finesse of the system increases.

Limiting the effect of the major drift elements (which have been described above) in low finesse cavities is rather straight forward; with careful construction, simple environmental isolation of the cavity will cut down on interior temperature fluctuations due to the outside air mass. Of course, electronic stabilization can be very effective for this type of system.

For cavities with relatively higher finesse (upwards of a few hundred), a more satisfying, if somewhat more difficult, stabilization method is to thermally compensate the cavity head for thermal changes of all kinds affecting the cavity resonances over some normal operating temperature range. (A well designed thermal servo whose inverse bandwidth is much smaller than the thermal propagation time of a heat pulse of finite duration and amplitude will continue to regulate the cavity temperature near the thermal noise fluctuation limit without external isolation). While isolation may become necessary when thermal overload of the regulation circuit occurs due to environmental considerations, the addition of electronic tracking circuits, which can enhance stability for some applications, should be optional with the capability of being switched out when necessary.

Summary

All interferometric spectrum analyzers have sources of drift in the cavity resonance frequency. The primary sources of drift in SuperCavity, a high resolution Fabry Perot interferometer, have been examined. The major sources of this drift that are presently addressed (in order of least-to-most important) are:

- out-of-lock thermal servo circuitry
- thermal changes in the d_{31} piezo strain constant
- thermally-induced drift due to material expansion
- piezo creep from voltage changes

The minimum drift associated with these sources is about one quarter of a fringe FWHM at $\lambda = 800$ nm with the current system, but could increase considerably if environmental isolation from thermal sources is not carefully controlled. Means to alleviate or eliminate these problems have been suggested.

Other more artificial means, such as electronic tracking circuits, have also been discussed to lock the cavity resonance to a particular peak.

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