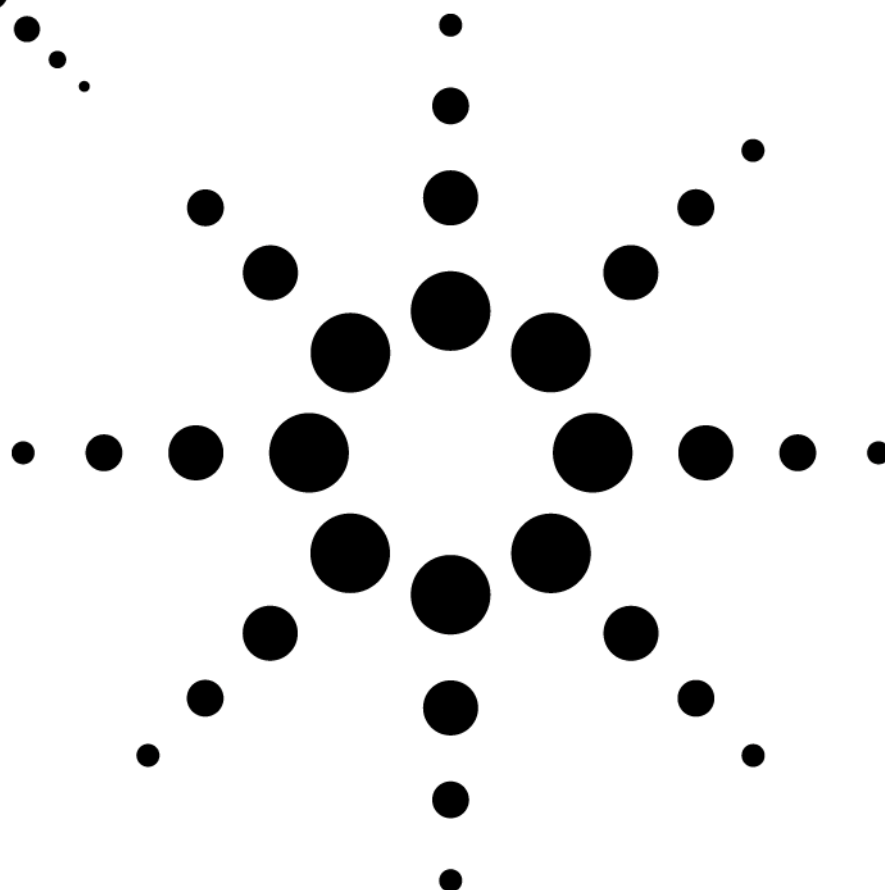
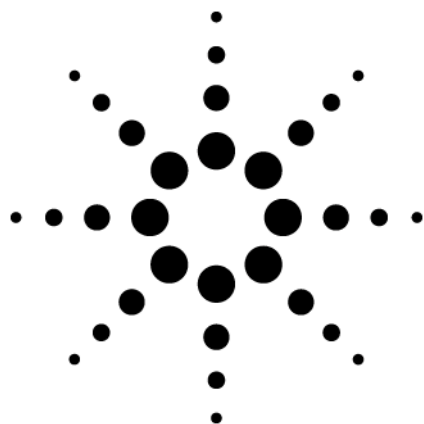


Measuring the group delay characteristics of narrow-band devices by the modulation phase shift method



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Introduction

This white paper provides a conceptual framework for selecting the wavelength step size and the modulation frequency for relative group delay measurements of narrowband optical components by the modulation phase shift method. With this understanding you can effectively measure group delay ripple, avoid aliasing errors, and improve the repeatability (reduce the noise) of chromatic dispersion and relative group delay measurements.

Background

The Agilent 86037C and 86038A measurement systems employ the modulation phase shift method. Light is intensity modulated with an RF tone and applied to the device under test. The transmitted (or reflected) signal is detected to recover the modulation envelope, and the envelope phase is measured relative to the RF source. Any change in the *group delay* $\Delta\tau$ of the test device produces a corresponding change in the modulation phase. In practice, the wavelength is stepped or swept over a small interval and the corresponding change in the group delay $\Delta\tau$ is calculated from the measured change in phase according to:

$$\Delta\tau = \frac{\Delta\phi}{360} \cdot \frac{1}{f_m} \quad (1)$$

where $\Delta\phi$ is the phase change in degrees produced by a small wavelength step and f_m is the modulation frequency in Hz. The first term on the right side of equation (1) is the number of cycles of modulation phase shift produced by the wavelength step, and the second term is the time period of a single RF cycle ($1/\text{freq} = \text{period}$).

The attribute called *dispersion* is defined by:

$$D = \frac{\Delta\tau}{\Delta\lambda} \quad (2)$$

where $\Delta\tau$ is the change in group delay in seconds corresponding to a change in wavelength $\Delta\lambda$ in meters. In practice, the dispersion is expressed in units of picoseconds per nanometer (ps/nm), where $1\text{ps}=10^{-12}$ seconds.

The *dispersion coefficient* is obtained by dividing the dispersion value by the length of the fiber:

$$D_{\text{coeff}} = \frac{1}{L} \cdot \frac{\Delta\tau}{\Delta\lambda} \quad (3)$$

where L is the length of the fiber. The dispersion coefficient is usually expressed in ps/nm-km.

Combining equations (1) and (2), we arrive at:

$$\Delta\phi = 360 \cdot D \cdot f_m \cdot \Delta\lambda \quad (4)$$

This shows that the amount of phase change measured in response to a wavelength step is the product of device dispersion, modulation frequency and wavelength step.

Lower limit on the wavelength step and the modulation frequency

The impact of the instrumentation phase noise ‘floor’ can be expressed by adding a phase noise term to equation (4):

$$\Delta\phi_{\text{total}} = (360 \cdot D \cdot f_m \cdot \Delta\lambda) + \Delta\phi_{\text{noise}} \quad (5)$$

Equation (5) shows that as the *product* of dispersion, modulation frequency and wavelength step grows smaller, the impact of phase noise increases. Measurement of group delay ripple often involves reducing both the modulation frequency and the wavelength step to achieve a suitably high wavelength resolution. Equation (5) warns us not to reduce them more than necessary.

Upper limit on the wavelength step and the modulation frequency

The *upper* limits on both modulation frequency and wavelength step derive from two considerations. The first is the need to resolve group delay variations that are closely spaced in wavelength, e.g., group delay ripple. The second is the requirement that the change in phase produced by a wavelength step must fall entirely within the alias-free range of the RF phase detector. One or the other of these considerations will dominate, depending on the device under test.

We examine the resolution issue first. Two measurement system parameters directly affect the resolution. The first is the wavelength step size, and the second is the modulation frequency.

Regarding the wavelength step size, suppose we are measuring group delay ripple that has a period of 0.1nm. To resolve the ripple, we need a wavelength step smaller than 0.05nm, and ideally as low as 0.01nm. Of course, lowering the wavelength step eventually raises the noise level as predicted by equation (5).

The wavelength resolution of group delay measurements is also affected by modulation frequency, as shown in Figure 1. The figure comes from T.Niemi et al., "Limitations of the phase shift method in measuring dense group delay ripple in fiber Bragg gratings", *IEEE Photonics Technology Letters*, vol.13, no.12, p.1334, December 2001, and also *Symposium on Optical Fiber Measurements (SOFM)* held at the National Institute of Standards and Technology (NIST) in September 2000 (page 165).

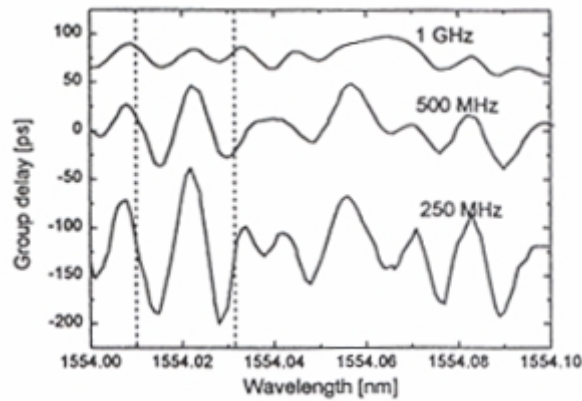


Figure 1 - Curves of group delay ripple measured with three different modulation frequencies, reprinted from T.Niemi et al. (cited above).

To achieve a high-resolution measurement of group delay ripple, the modulation frequency should be low enough that the modulation sidebands ride up and down the group delay ripple as a pair, as illustrated in Figure 2.

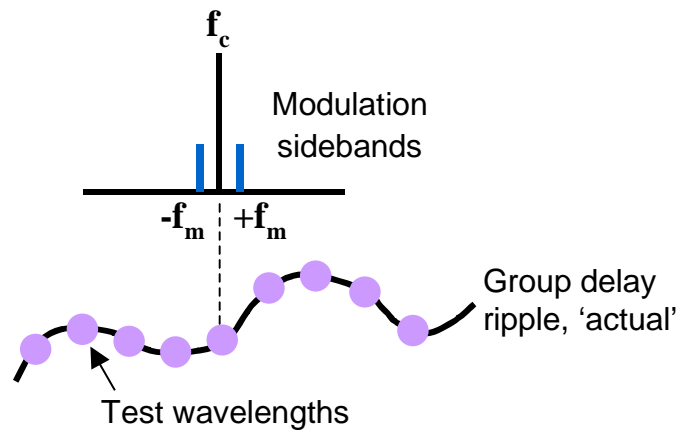


Figure 2 - Selecting the modulation frequency for measurement of group delay ripple.

The three-dimensional graph in Figure 3 shows the selection of wavelength step and modulation frequency to achieve high wavelength resolution. Reduction of only one of the two may fail to achieve the desired resolution and simply raise the noise floor.

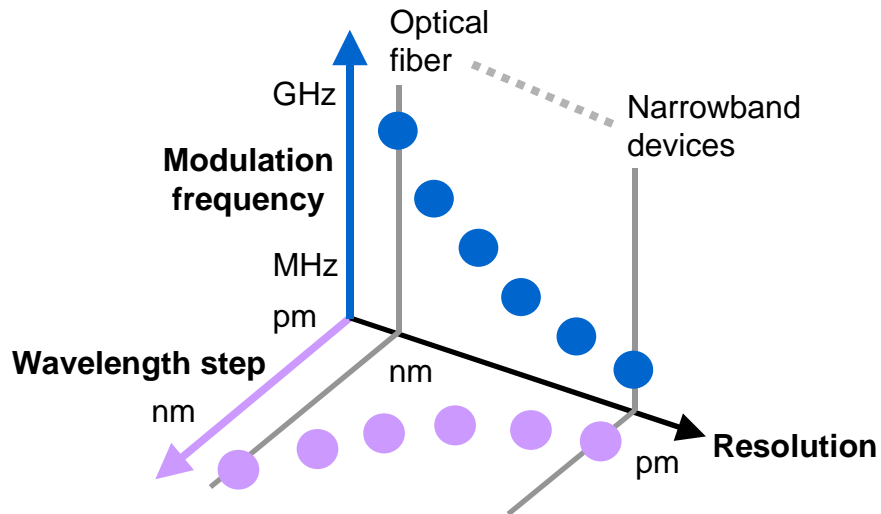


Figure 3 - Adjusting wavelength step and modulation frequency to achieve a desired resolution.

The graph shown in Figure 4 is an aid to selecting the wavelength step and modulation frequency for measurement of fine group delay ripple. To use the chart, follow these steps:

- 1) enter the x-axis at the estimated period of the group delay ripple.
- 2) draw a vertical line to the curve representing the desired number of measurement samples per period of the group delay ripple.
- 3) draw a horizontal line to the left and right hand axes. Read the wavelength step and the modulation frequency from the left and right vertical axes, respectively.

Creation of the chart assumed that the double-sided spectral width of the RF modulation spectrum is exactly the same as the wavelength step size. Of course, in some measurement situations it may be appropriate to take smaller wavelength steps than the chart would suggest (over-sample), to allow for post-smoothing of the data as a way to mitigate trace noise.

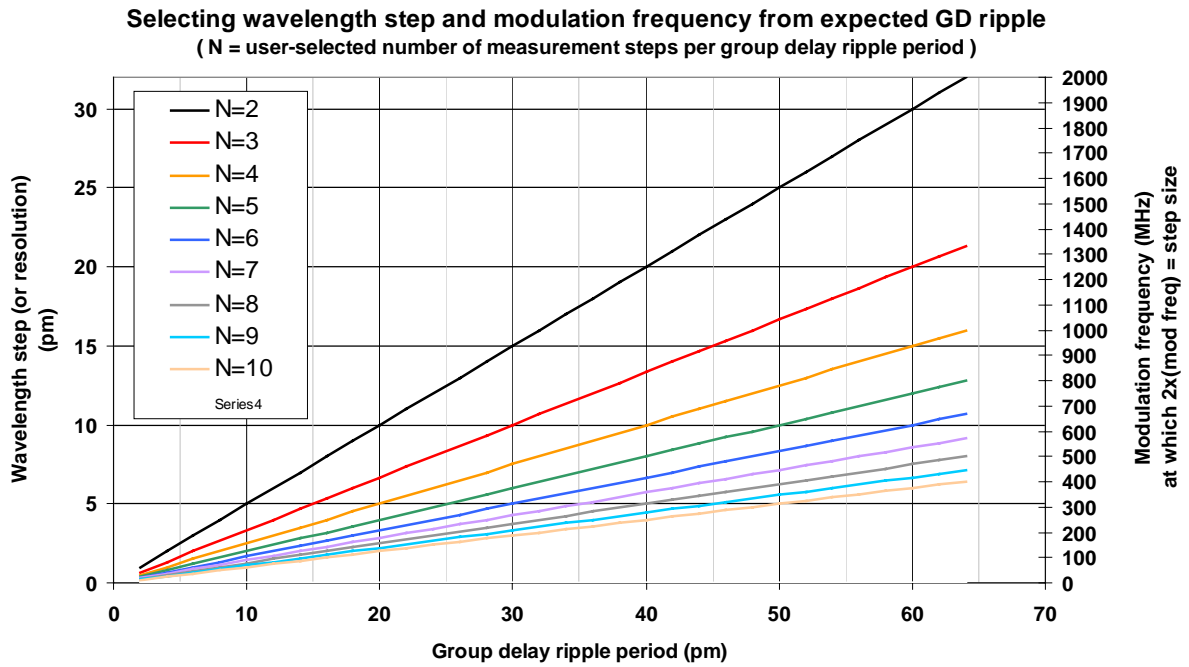


Figure 4 – Chart for selecting the wavelength step and modulation frequency for measurement of group delay ripple.

Modulation frequency and wavelength step size are also limited on the high end by the range of the phase detector. Exceeding the range of the phase detector causes an aliasing error. The governing equations are:

$$\Delta\phi = (360 \cdot D \cdot f_m \cdot \Delta\lambda)$$

$$\Delta\phi < \pm 180 \tag{6}$$

The phase detectors used in the Agilent 86037C and 86038A system have a range of ± 180 -degrees. After each wavelength step, the phase detector is zeroed to make the entire ± 180 -degree range available for the next step. If a wavelength step produces a phase change larger than ± 180 degrees, the phase detector loses the history of the *actual* phase change and gives us only an *apparent* phase change. For example, if a wavelength step produces an actual phase change of positive 185 degrees, it will be interpreted as *negative* 175 degrees. This is an aliasing error.

The extent to which an aliasing error affects the shape of the measured relative group delay curve depends upon the details of both the test device and the measurement setup parameters. Use care, as it is possible for aliasing errors to go entirely unnoticed. Agilent provides an Excel spreadsheet based calculator for estimating the maximum allowable step size. It is called the *Wavelength Step Calculator for Modulation Phase Shift CD Measurements* and can be found in the Library section of the public Agilent product web pages for the 86037C and the 86038A. Both instruments provide an 'automatic modulation frequency selection' feature to avoid aliasing error in *fiber* measurements.

Control of resolution and noise

When measuring low-dispersion, narrowband devices at high resolution, we face the noise limit described by equation (5). Figure 5 provides an intuitive guide to the management of this noise. The brick walls represent limits. The left-right axis of the figure represents the repeatability (conversely the trace noise) of the group delay measurement. The upper half of the figure shows the modulation frequency and wavelength step settings. We reduce them to achieve better resolution (movement to the right in the figure), but eventually the trace becomes noisier and the test time increases.

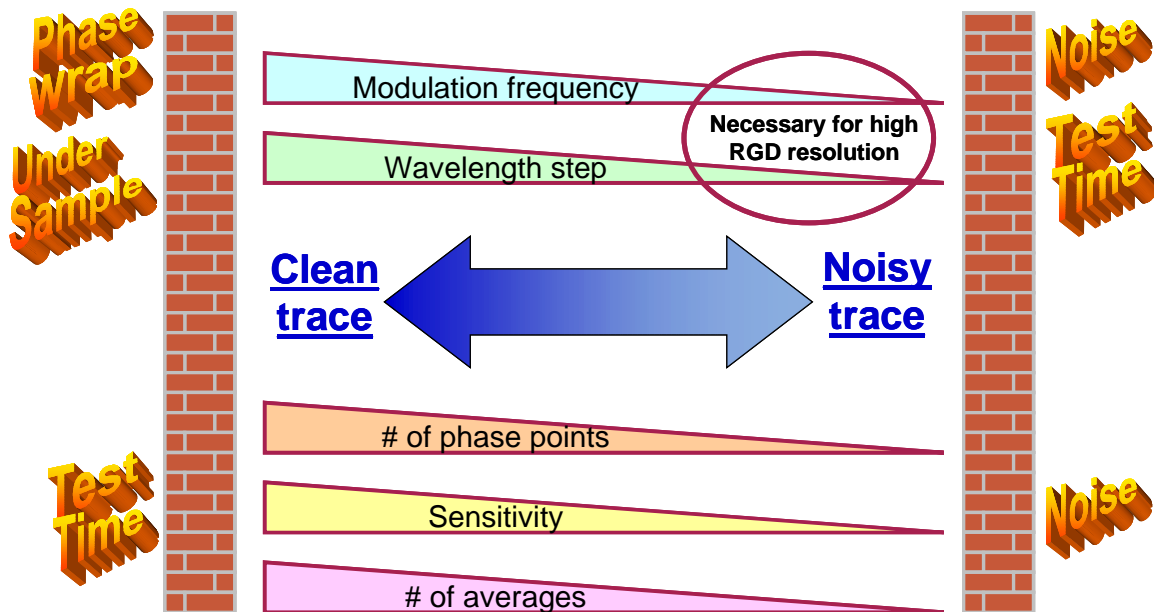


Figure 5 – Managing noise in high-resolution measurements

The bottom half of Figure 5 shows three setup parameters that can be adjusted to push our measurement back toward the 'clean trace' (low noise, high repeatability) side of the figure. We can increase the number of phase points in the network analyzer sweep at each

wavelength, achieving a phase noise reduction through the averaging of all of these phase samples. We can also increase the sensitivity, which reduces the IF bandwidth of the network analyzer. Finally, in extreme cases, we may elect to average multiple sweeps of the network analyzer. This last technique is rarely necessary. Naturally, these noise control parameters affect the measurement time.

Selecting setup conditions for a new type of narrowband device

Identifying the best setup conditions is a process that should be performed *once* before testing a new class of device. Once the appropriate setup conditions are determined, they can be saved and used for all future measurements of that type of device.

When the dispersive characteristics of the test device can be estimated in advance, one can use the equations presented earlier to compute the appropriate setup conditions. For example, if the device is expected to exhibit fine group delay ripple of a particular wavelength period, one can reduce wavelength step and modulation frequency accordingly.

The procedures presented below are empirical. They assume that the test device is a filter and that we have no estimate of its dispersive characteristics. We know only the -3dB wavelengths of the filter passband. In general terms, the process involves progressively reducing the wavelength step and the modulation frequency to reveal the actual shape of the relative group delay curve. Of course in the limit, reducing the wavelength step and modulation frequency will cause the phase noise to dominate the measurement.

It can be helpful to think of this process in terms of achieving the best exposure conditions in taking a photograph. Professional photographers 'bracket' the shot by taking several pictures with different camera settings. With experience, the bracketing process takes fewer snaps and less time.

The biggest measurement challenge is posed by a low-dispersion device that exhibits fine group delay ripple. This requires the selection of relatively low modulation frequency *and* small wavelength step size, a combination that allows the noise to dominate when the dispersion is small. Equation (5) describes this relationship.

Method A – Test (step) mode

The general approach is to perform several measurements using different wavelength step sizes and modulation frequencies and observe the differences in the results. Specifically, set the start and stop wavelengths to correspond to the 3dB band edges of the filter passband. Estimate the wavelength step required to reveal the expected group delay variation. Set the equipment for this step size and choose a modulation frequency having a comparable spectral footprint (it may be helpful to use Figure 4). Perform a measurement. Perform additional measurements with variations of modulation frequency. Which settings give better visibility of fine group delay variations? Beyond which settings is the improvement in resolution cancelled out by an increase in trace noise?

Iterate between the wavelength step and modulation frequency experiments in order to find the global optimum. Use the controls described in the bottom of Figure 5 to mitigate the noise to the extent possible.

Method B – Preview (swept) mode

The approach is the same, but the instrument is operated in the Preview or Swept mode. In this case, we refer to the wavelength resolution rather than the wavelength step. The wavelength resolution is the wavelength range divided by the number of phase samples that is taken during the wavelength sweep.

Conclusion

First-time measurement of the dispersion/group delay characteristics of a new type of narrowband component requires special attention to the selection of wavelength step size and modulation frequency. The process of making these selections has been described in a qualitative way and the underlying mathematical relationships have been discussed.

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