Swept Laser Interferometric Interrogation

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ABSTRACT

A high-speed, swept-laser interferometric interrogation approach is introduced. Dynamic measurements of weak Fabry-Perot or Fizeau type interferometers with gap ranges of 50 um to 1 mm up to 70 Ksamples per second are demonstrated and discussed. Displacement resolution is < 1 pm/rt-Hz. This has application with MEMS and FPPI type sensors.

Keyword List: *Swept Laser, Interferometer, Interrogation, Demodulation*

1. OBJECTIVE / DEFINITION OF PROBLEM

The ultimate objective is to measure interferometric phase from remote small-"gap" interferometers to make high speed (10's of KHz) precision measurements. Typical gap interferometers are formed by weak Fabry Perot cavities with typical gap ranges from 20 to 1000 um. A typical representation of such an interferometer is shown in figure 1. These are often known as "gap" or FPPI type interferometers.

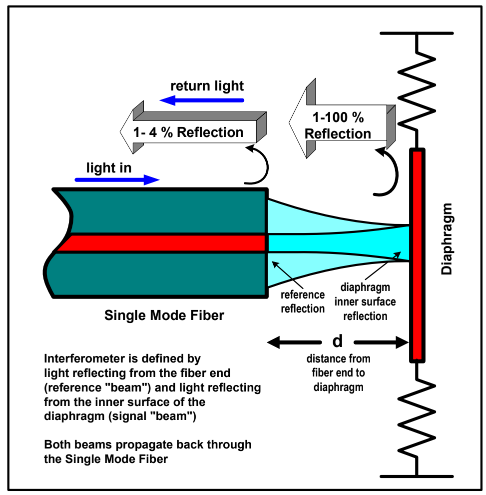

Figure 1. Remote Interferometer Sensor formed by gap between fiber end and diaphragm

Generally the most effective approach to realize high fidelity measurements of optical phase variations of an interferometer is to obtain quadrature readings from the interferometer and then use inverse trigonometric approaches to measure the optical phase.

The desired approach to obtain quadrature terms is to implement some type of phase modulation carrier, typically known as a Phase Generated Carrier[1] (PGC), then process that signal to obtain quadrature terms. Ideally, this modulation approach is best performed external to the interferometer so that the sensor can be "passive" and remote. A desirable remote sensor interrogation approach is shown in figure 2 where an optical source wavelength or frequency modulation approach is implemented.

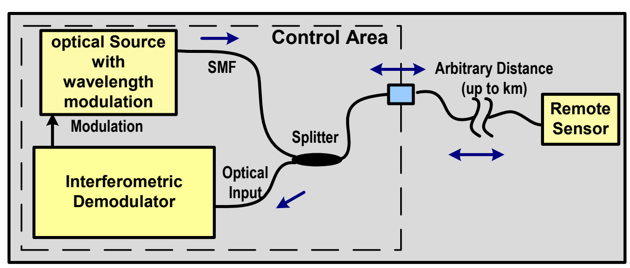

Figure 2. Interrogation Approach for Remote Gap Sensor

Basically the approach involves producing a PGC via sinusoidal modulation of the phase, where modulation phase excursions controlled to a particular level (generally 2π). Sensor (phase) signals are contained as sideband information to the PGC. Quadrature terms are extracted via appropriate sampling and arithmetic reduction. Demodulation is accomplished with an inverse trigonometric digital approach[2].

The problem with small gap interferometer "interrogation" occurs when optical gap distances are less than 1 mm, which is generally the case. In order to produce a sufficient modulation index for the phase generated carrier interrogation, laser wavelength excursions of a few nm to tens of nm are required. Until recently very few optical sources or *swept lasers* with such capability have been commercially available; and of those available (as stand alone instruments), costs were prohibitively high to consider for use in a commercial interrogator.

Recent advances in swept laser technology serving both medical imaging (OCT) and spectrometry applications have propelled their development and commercialization to the point where these devices are now more cost effective through higher volume demand and new suppliers competing for the market. Given this trend, the prospect of implementing swept lasers for interrogation of gap sensors enhances the potential for commercial viability, and the interest in this research.

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1.1. Ranges of Modulation Required for Interferometric Interrogation

The relationship between optical phase change wavelength (or frequency) modulation of the swept source is defined.

$$\Delta\phi = \frac{2\pi n}{\lambda^2}\Delta\ell\Delta\lambda \quad \text{or} \quad \Delta\phi = \frac{2\pi n\Delta\ell\Delta f}{c} \qquad \textbf{(Eq. 1)}$$

where
$\Delta\phi$ = the optical phase change (in radians)
$\Delta\ell$ = the optical path mismatch length of the gap sensor
$\Delta\lambda$= Optical wavelength change of the source
Δf = the optical frequency variation (caused by wavelength variation)
n = index of refraction of the gap
c = speed of light in vacuum

Expected ranges for gap sensors span from perhaps 25 um to 1000 um. If the interrogation approach calls for a 2π peak to peak phase excursion the following modulation ranges for the swept source can be determined. Here a gap is assumed of index of 1 (air) and light double passes the gap. Note the frequency range calculation is independent of wavelength.

GAP	Wavelength Range 1310 nm (center)	Wavelength Range 1550 nm (center)`	Frequency Range
25 um	34 nm	48 nm	6000 GHz
50 um	17 nm	24 nm	3000 GHz
100 um	8.6 nm	12 nm	1500 GHz
200 um	4.3 nm	6.0 nm	750 GHz
400 um	2.1 nm	3.0 nm	375 GHz
800 um	1.1 nm	1.5 nm	188 GHz

1.2. Basic Requirements for Optical Source with Wavelength Modulation

Ideally, one would want an optical source with wavelength sweeping capabilities of the following characteristics;

1. Low Phase noise (ideally < 10 urad/rt Hz with OPD up to 2 mm.
2. Wavelength sweep range up to 60 nm.
3. Sweep Rates of up to 70 KHz
4. Source is intensity invariant over sweep range
5. Source should be sold as a component or assembly (not an instrument), and have the future capability of being low to moderate cost.

2. SWEPT LASER SELECTED FOR INVESTIGATION

The first known manufacturer of swept lasers possibly suitable to the basic requirements described above was Axsun Technologies, in Billerica, MA. They manufacture a family of products ranging from micro-spectrometers, Optical channel monitors and "sensor interrogators." One of the key ingredients of their spectrometers and interrogators involves a swept laser assembly. This swept laser assembly incorporates design features involving a temperature stabilized active semiconductor gain medium and an electronic tunable MEMS Fabry Perot type filter, where these elements are contained in a standard 14 pin Butterfly package as shown (cover open) in figure 3. The assumed design approach[3] is shown in figure 4 depicting the key operative elements (based on US patent 7415049).

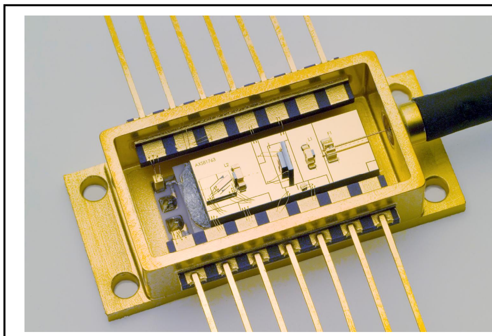

Figure 3. Axsun swept laser assembly

Optical gain for the cavity is provided with a SOA with a back reflector. Light propagates through a tunable MEMS filter[4] which is slightly tilted in the optics path. The light is focused into a "pigtail" fiber comprising either SMF or PMF with a broadband partial reflector at some predetermined length along the fiber. This broadband reflector completes the laser cavity. Fast tuning of the output wavelength is provided by the low-mass electrostatically tuned MEMS filter.

The useful features of this design with tilted filter and extended cavity making it attractive for the gap sensor interrogation applications are as follows:

- Lower threshold drive for the laser;
- Broadened tuning range (tests by Optiphase show 100+ nm range);
- Minimize mode hopping noise by the decrease of longitudinal cavity mode spacing;
- Design approach is suited to low to moderate cost manufacturing (assuming volume).

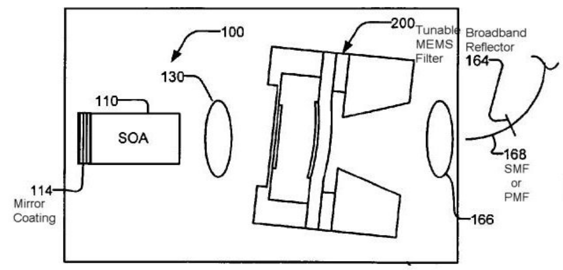

Figure 4. Laser Cavity Design Approach

2.1. Lasers Used for Testing

Two different swept lasers were implemented. The first dubbed "TLM 499" was manufactured by Axsun to address spectrometry measurements (broader linewidth). The second unit "TLM 834" was a narrower linewidth device, generally useful for Optical Coherence Tomography. Basic characteristics of both units are as follows.

TLM 499

- Short Coherence Length (~ 1.5 mm)
- Very broad tuning range (1335 to 1560 nm)
- ~ 5 mW output, SMF output pigtail
- Fast tuning ~ 50 KHz (sinusoidal drive)

TLM 834

- Longer Coherence Length (~ 11 mm)
- Broad tuning range (1255 to 1365 nm)
- ~ 7 mW output , SMF output pigtail
- Fast tuning (tested out to 70 KHz, sinusoidal drive)

Characterization Testing of both swept lasers.

Voltage to wavelength tuning curves are shown in figure 5. Both have a parabolic response as expected for MEMS electrostatic actuated devices. Spectrums and associated coherence functions were measured at spot wavelengths. For TLM 499 the wavelength was 1517 nm. For TLM 843, the wavelength was 1305 nm.

The coherence function (single sided) was measured with a path tunable interferometer and is shown in figure 6. The spectrums of both devices are shown in figure 7.

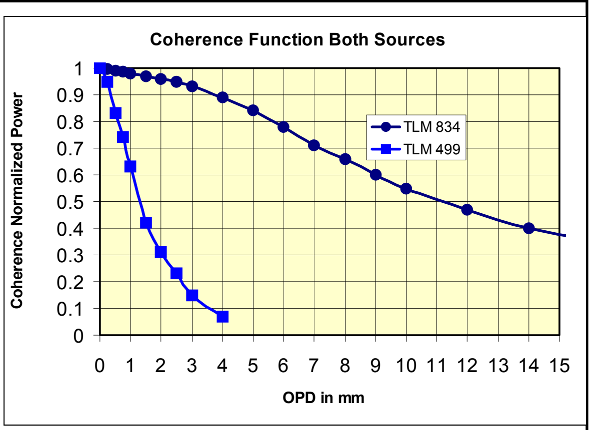

Figure 6. Normalized coherence of Axsun Swept Lasers, TLM499@ 1517 nm, TLM834 @ 1305 nm

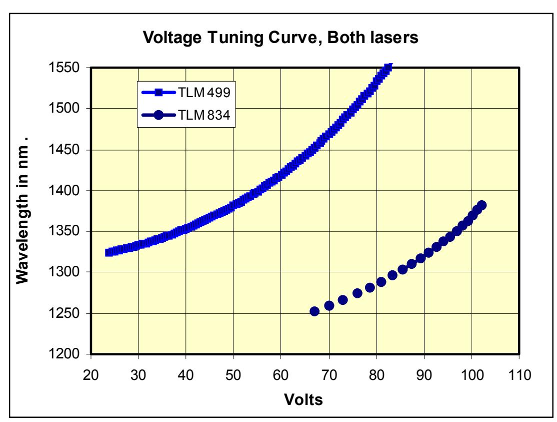

Figure 5. Voltage Tuning Curve for Axsun Swept Lasers, TLM499 and TLM834

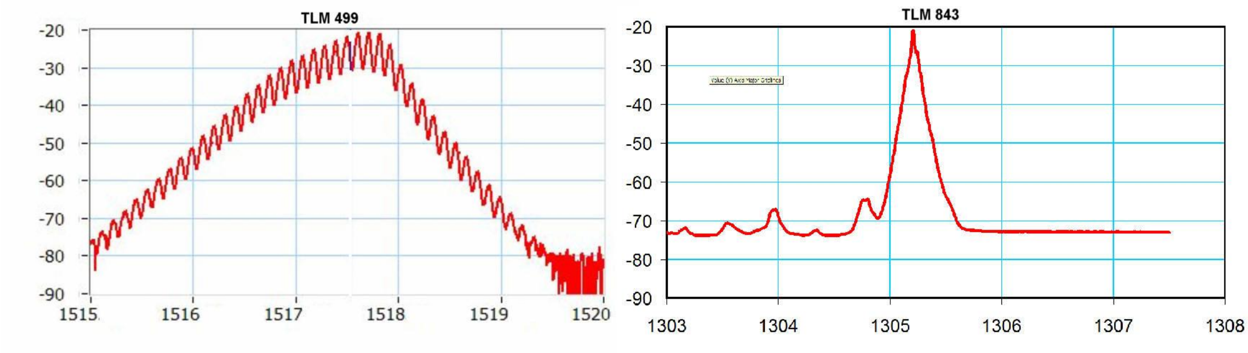

Figure 7. Spectrums of TLM 499 (left) and TLM 843 (right). Horizontal scale in nm, vertical scale in dB optical

The ripple in the spectrum for TLM 499 is consistent with multiple longitudinal mode spacing. It is assumed that multiple lines exist in TLM 843, however the spectrum analyzer resolution of 10 pm used to make the measurement wasn't sufficient to resolve these. Further, it appears that TLM 843 only resolves down to -50 dB from the peak wavelength which likely constitutes some type of an ASE limit.

3. INTERFEROMETER TEST ARRANGEMENT

Figure 8 shows the test arrangement used to assess performance of the Axsun swept laser assemblies when used as the wavelength swept optical source for interferometric interrogation of a gap type interferometer.

Light from the swept laser (TLM Tunable Laser) is injected to a circulator (for isolation and signal efficiency), and then to a gap type test interferometer. The center wavelength is set by a tunable DC voltage supply and a modulation signal (50 KHz for TLM 499 AND 70 KHz for TLM 834) is provided by the modulation drive of the OPD-4000 Optical Phase Demodulator[5].

The OPD-4000 was used to perform interferometric modulation / demodulation of the simulated gap interferometer. It is a DSP based large-angle optical phase demodulator implementing a PGC modulation process with a modulation depth of π radians. Optical phase is determined via quadrature recognition and inverse trigonometric calculations with dynamic range enhanced via fringe counting. The demodulation sample rate is equal to the modulation frequency.

A simple passive drive circuit was implemented to sum the AC and DC signals to the drive the tunable lasers. A separate signal generator is used to provide simulation test tones to the test interferometer to analyze interrogated or demodulated signal response characteristics.

The test interferometer was configured such that the gap between the two reflections forming the interferometer could be adjusted via translation of the reflector to test for various gap sizes. A white-light interferometer was used to calibrate the translation stage micrometer readout to known gap displacement settings.

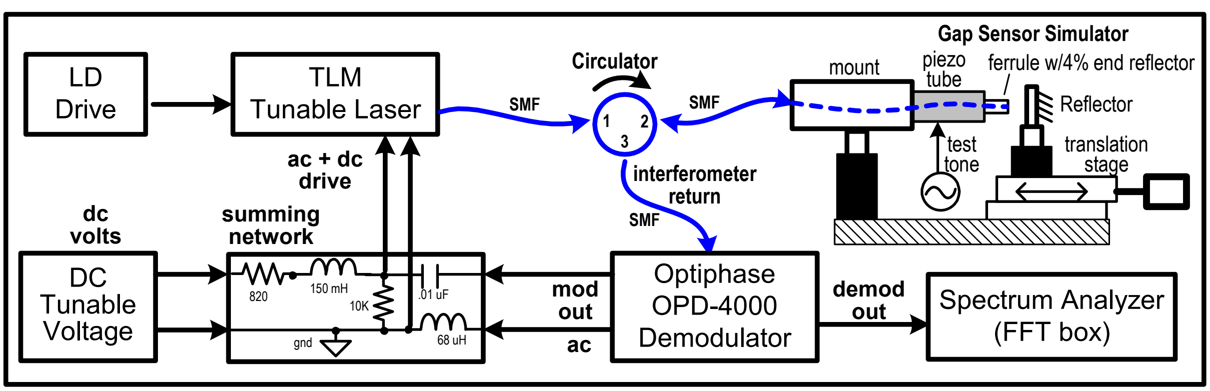

Figure 8. Test Arrangement used to evaluate the swept laser interrogation approach

4. TESTING FOR DEMODULATION FUNCTION AND PERFORMANCE

The overall plan for the testing was as follows.

1. Verify Modulation / Demodulation could be performed at 50+ KHz mod/ demod rates.
2. Test at various gaps and assess function and measure noise / resolution capability.
3. Test linearity of the demodulation process (at various gaps).

4.1. Verify Modulation / Demodulation

This somewhat perfunctory task was required to establish appropriate operating conditions for the Conditions for all testing

Center Wavelength:	TLM 499: 1511 - 1518 nm;	TLM 843: 1302 – 1308 nm
Modulation / Drive Frequency	TLM 499: 50 KHz;	TLM 843: 70 KHz
Demodulation Sample Rates	TLM 499: 50 KHz;	TLM 843: 70 KHz
Gaps Tested	50, 100, 200, 400, 800 um. (n=1)	

Observations

TLM 499
This laser had no observable degradation in its intensity versus wavelength for the various sweep ranges anticipated at the 50 KHz sweep frequencies. Also, this device was loaned to Optiphase (by Axsun) for only a short time and regretfully, the author (at the time) didn't think to evaluate this device at higher sweep frequencies, but plans to in a future effort.

TLM 843
This laser was more of an experimental device designed for Frequency Domain Optical Coherence Tomography (FD-OCT) applications with a narrower linewidth and was observed to have substantial intensity fluctuations (up to 40% at 40 nm excursions) in intensity over the intended wavelength sweeps when rates were applied greater than 20 KHz. These fluctuations are likely related to the gain / coherence collapse at the higher rates. It was further observed that these fluctuations didn't appear to be completely stable for repeat sweeps.

As the intent was to test the interrogation approach at 50 KHz (or higher), a decision was made to test at 70 KHz as this is the frequency limit of the demodulator used and there was no noticeable change in sweep degradation was observed between 20 to 70 KHz.

Both Lasers
Verification of demodulation was made for both units. For TLM 843 given the sweep intensity fluctuation at 70 KHz, there was the expectation that there would be some penalties on the performance evaluations, as pointed out in the next section.

4.2. Verify Modulation / Demodulation

One of the most important tests is to determine the threshold resolution ability of the interrogation approach. This involved first validating functionality, then make measurements of the demodulated optical phase noise and converting these values to equivalent displacements of the gap sensor. This was performed for both TLM swept lasers. Results are provided in figures 9 and 10.

Data from figure 9 (TLM 499) shows for short gaps (out to 200 um) shows an impressive resolution of 1-2 pm/rt-Hz. However for the larger gaps, this resolution creeps up to 15+ pm/rt-Hz mostly in consideration of the short coherence length of this source. Contrast this to data in figure 10. Here the results are more closely grouped where all gaps tested come in between 1 – 5 pm/rt-Hz. However the data here doesn't follow a logical scaling. For example the best performance is obtained at the 200 um gap and the 50 um gap produces the highest noise.

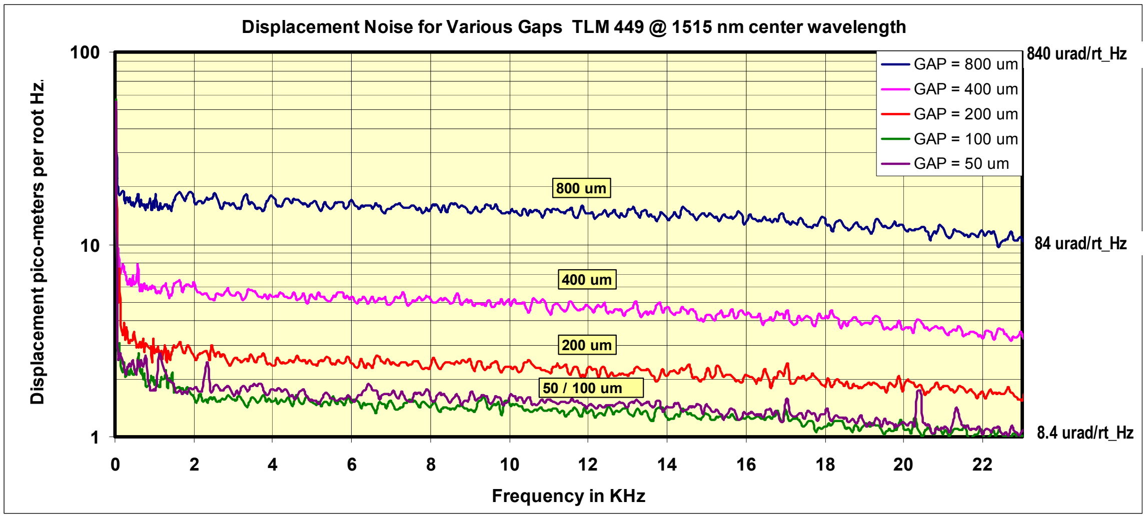

Figure 9. Displacement resolution using TLM 449 swept laser for gap ranges of 50 to 800 um. Right vertical axis shows equivalent phase noise.

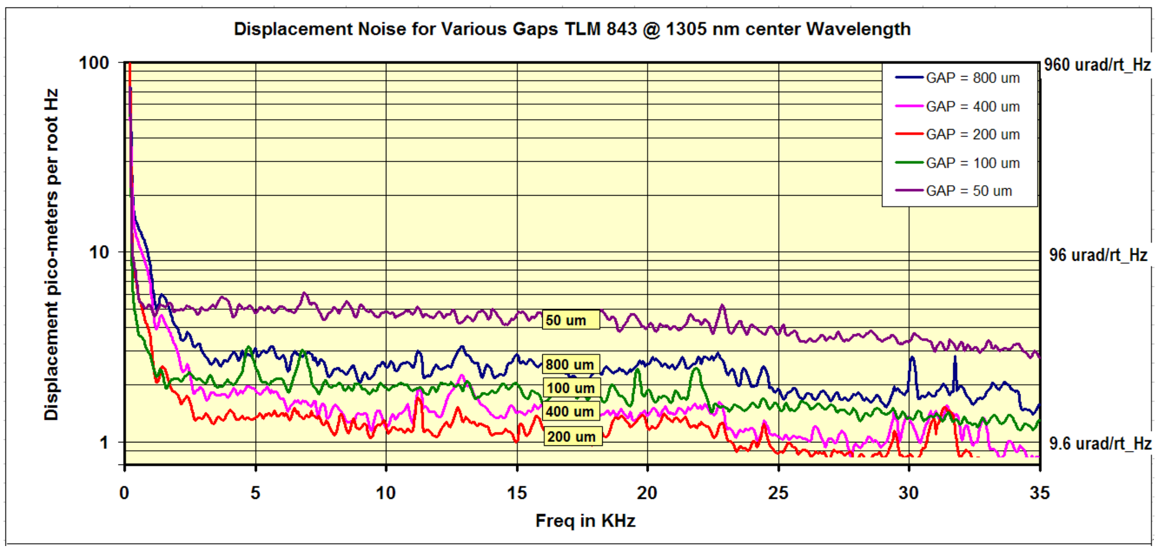

Figure 10. Displacement resolution using TLM 449 swept laser for gap ranges of 50 to 800 um. Right vertical axis shows equivalent phase noise.

The causes for the resolution variations seen in figure 10 relate most likely to the coherence collapse of the swept laser TLM 843 at the higher sweep rates (> 20 KHz), and excess RIN caused by intensity variations during the sweep, where some sweep ranges have more RIN than others. This investigation did not pursue the details sufficiently to resolve the specific issues.

Overall, it was determined that it is reasonable to believe that a swept laser interrogation of a gap interferometer should be able to attain a resolution of 1 pm/rt-Hz, and further, there is room for design optimization to attain higher performance.

4.3. Linearity of the Demodulation Process

Some level of non-linearity or demodulation distortion is assumed. Some in part due to the demodulator (OPD-4000) which when implemented to produce "proper" PGC signals produces about 0.1% distortion. However the processes used with the swept laser interrogation approach provide a few extra non-linearities as follows.

1. Non-linear modulation function (see figure 5) due to the electrostatic MEMS actuator characteristic. *Note: in this effort, no effort was made to pre-distort the drive to compensate for this.*
2. Intensity variations over the sweep. Both lasers exhibited this. TLM 499 had a small ripple in its swept spectrum (due to a feature designed to support spectroscopy metrology). TLM 843 has a large ripple due to coherence collapse at the fast sweep rates.

Distortion tests were run for the various gap distances (50 to 800 um) with a sinusoidal input signal applied to the piezo tube (figure 8) to modulate the gap interferometer (to simulate a sensed signal) being nominally 1 KHz at a level of pi radians peak to peak. Distortion measurements made for the two different lasers are reported.

TLM-499: 0.2% to 2%. *The higher distortion numbers were seen for the shorter gaps which require a larger wavelength sweep. This is mainly due to the wavelength ripple discussed above and easily obviated by removing the design "feature."*

TLM-843: A few percent . *This is no surprise due to the large amplitude instabilities over the wavelength sweep ranges. For this reason, this laser, which is optimized for FD-OCT is not optimized for swept wavelength interrogation.*

5. CONCLUSION

An effective and high resolution interrogation approach for interferometric sensing of gap sensors has been identified and demonstrated. Of particular interest and possible uniqueness, is the ability demonstrated to interrogate small gap sensors where gaps are less than a few hundred micro-meters. For these small cavity distances, traditional approaches to modulate the wavelength of a laser using cavity piezo elements or injection current modulation of diode lasers cannot produce nearly the wavelength tuning range (few nm to 10's of nm) required for interrogation.

It is these small gap sensors which are envisioned to be the most likely sensors to be produced in large volumes, as these type sensors can be mass produced to high precision using MEMS manufacturing techniques where gap ranges for type sensors rarely exceed 500 um, and more commonly are found to be 10's of um.

This interrogation approach although shown for single sensor implementation is also suited to Time Division Multiplexed (TDM) interrogation of multi-element sensors or arrays. Market analysis is underway related to the consideration of commercialization of this technology.

ACKNOWLEDGMENTS

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