Very High Sensor-Density Multiplexing using a Wavelength-to-Time Domain Reflectometry Approach based on a Rapidly Swept Akinetic-Laser

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ABSTRACT

We demonstrate a scheme for the interrogation of arrays of FBG sensors based on a Swept Laser Distributed Sensing system which can achieve 1000 sensors or more in a single fiber, while retaining the sensitivity and repeatability expected with FBG sensors of better than 0.5 με and 0.05 C. The system utilizes an 'akinetic' wavelength swept source and an arrival time-dependent detection approach to allow potentially 1000s of very low reflectivity FBGs to be monitored via a form of Wavelength-to-Time Domain Reflectometry. We demonstrate the interrogation of 250 gratings in a system architecture designed to support 1000 gratings.

Keywords: Fiber Bragg Gratings, Akinetic Laser, Wavelength-to-Time Domain Reflectometry.

1. INTRODUCTION

Optical fiber has been used for sensing applications for over 30 years, and as a technology platform, it has earned an important place alongside electrical sensing in the overall market due to several key advantages, including relative environmental robustness, small size, and distributed/multiplexing capabilities. FBGs in particular have found wide application [1] due to their inherent versatility and sensitivity and multiplexing attributes. However, there have been limitations in spatial density and number of sensors that can be interrogated on a single fiber using multiplexing approaches. Using "conventional" wavelength multiplexing over a wavelength band of say 100 nm enables on the order of 20 to 50 sensors maximum depending on the 'operational wavelength range' required by each sensor. FBG sensor arrays based on a combination of WDM and TDM schemes have been reported that improve the sensor count. These systems generally rely on the injection of pulsed broadband light, and the use of TDM analysis to separate out groups of FBGs reflections which span the same range of set of nominal wavelengths, but which are spatially separated along the fiber. The underlying wavelength determination in this case is via a spectral filtering / spectrometer approach, with the TDM processing allowing the separation (demultiplexing) of the sensor groups in the time domain. These approaches, and other novel approaches such as code-division based schemes [2] can increase sensor count in the array, but only hundreds of sensors have been demonstrated to date. However, there are numerous applications that desire hundreds or even over a thousand sensors in a single fiber.

In this paper we describe an approach to interrogating a very dense array, of potentially thousands of weakly reflecting FBG elements using a rapidly swept laser. The scheme converts the return signals generated via a wavelength swept / pulsed optical input into 'arrival time signatures' for each sensor, thus essentially converting the wavelength domain scan into an OTDR-type arrival time domain detection format. The element that enables this capability is a new form of 'akinetically' swept, all-semiconductor laser, which was initially developed applications in WDM telecom systems [3]. The unique attributes of this akinetic laser that enables this Wavelength-to-Time Domain Reflectometry (WTDR) interrogation approach are i) rapid scan capability, ii) wide wavelength scan range, and iii) extremely high precision scanning. This later attribute provides the basis for the transpose from wavelength-to-time in the detection system.

2. SYSTEM ARCHITECTURE

In the Swept Distributed Sensing approach described here, the interrogation is completely time-based: Both the spatial position and the FBG wavelength are encoded uniquely into the time domain, yielding a true Wavelength-to-Time Domain Reflectometry approach. Figure 1 illustrates the concept: The sensor array comprises a series of sub arrays of

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very low reflectivity FBGs (-30dB). The wavelength of the FBGs in each sub array are nominally the same (λ_1 - λ_n), and all fall under the sweep range of the laser. As the laser scans over a FBG element, the optical refection manifests itself as a reflection 'pulse' that occurs at a time (relative to the start of the laser scan/pulse) which is dependent on both the grating center wavelength and the optical group delay from the laser to the sensor FBG. As the spatial position and nominal center wavelength of each grating can be preset in the design of the system, the array can be configured to 'assign' the FBG returns to a given 'arrival time window'. The 'window' identifies the sensor in question, whereas the exact timing of the arrival determines the grating wavelength shift due to a measurand perturbation (+/- dλ). Consequently, both the spatial position and the FBG wavelength are encoded uniquely into the time domain: The system thus takes the form of an OTDR-type Wavelength-to-Time Domain Reflectometry sensing approach. Due to its scan speed and wide-bandwidth, the laser system has the versatility to allow a variety of different 'formats' of sub-array length, number of sensors, grouping and nesting of sensors.

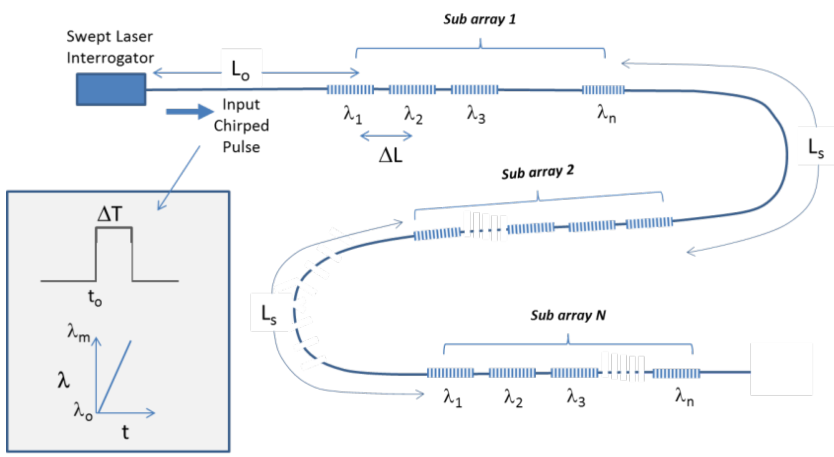

Figure 1. Schematic of the Swept Wavelength to Time Domain Reflectometry Scheme for FBG arrays

As illustrated in Figure 1, the input to the array is in the form of a wavelength-chirped pulse. As the akinetic laser can be swept at rates in the 100's of kHz, the swept occurs very rapidly; as fast as 1 to 10 μs is possible. This sweep time is in the same range as the time of flight of the optical signal in the fiber for many infrastructure or oil and gas applications for example. As a result, a single sweep can be run, with a time gap to allow reflections from multiple segments of identical-wavelength sensors to return, before the sweep repeats. Further, since the sweep is akinetic, it is very flexible, and alternative formats are possible, for example – by running 'sub-sweeps' over shorter wavelength ranges with gaps, shortening of the fiber segment length between sub arrays can be achieved. Furthermore, as the FBGs used are very low reflectivity, and each sub array is read progressively, the accumulated effect of sensor shadowing, which leads to crosstalk, can be accurately determined from the earlier-in-time responses: i.e, the impact a given FBG has on later signals can be decomposed, rendering the later FBGs without any spectral shadowing.

In the system reported here, the sensor groupings are produced with very low reflectivity gratings, ensuring that adequate light continues through the fiber to illuminate the subsequent sensor groups. As discussed above, in operation, as the laser scans over a the wavelength of a given FBG element, the optical refection signal manifests itself as a Gaussian-type 'pulse', determined by the convolution of the laser profile and line-shape of the FBG, that occurs at a time relative to the start of the laser scan which is dependent on the grating center wavelength and the optical group delay from the laser to the sensor grating. The arrival times of the first sub array, t_j can be characterized by an equation of the form:

$$t_j = \left[\frac{(\lambda_j - \lambda_o)}{\Delta\lambda}\right]\Delta T + \frac{2n}{c}(j\Delta L + L_o) \qquad (1)$$

The subsequent sub arrays have arrival times that incrementally add to the previous sub-array, and also follow Eqn (1), but with the fiber length between sub-arrays, L_s, substituted for the input fiber, L_o (see Figure 1). In its most basic implementation, the laser duty cycle is 1/N to allow all FBG returns to be detected prior to the next laser pulse input to the system.

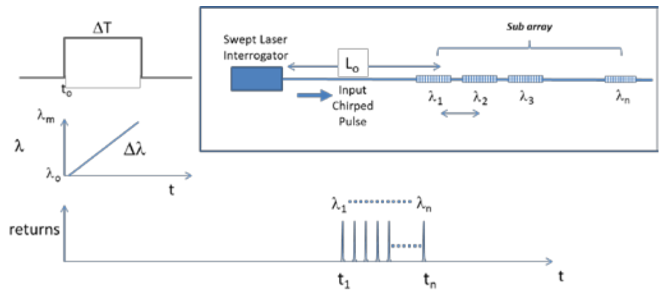

Figure 2. Illustration of the arrival times of the FBG returns for the first sub-array in the system of Figure 1.

3. RESULTS

As noted previously, the laser is an akinetically wavelength swept semi-conductor laser, manufactured by Insight Photonics [3,4]. Because the laser wavelength is determined by the currents applied to the laser, the laser is extremely repeatable from sweep to sweep, and from one sweep to another sweep considerably later in time. Indeed, testing has indicated that rather than multiple-pm level repeatability typical of mechanically tuned lasers (e.g., external mirrors/etalons), the akinetic laser has short and mid-term repeatability of better than ~100 fm (0.1 pm). Figure 3 illustrates the sub-picometer repeatability of individual points in a sweep for over 8000 sweeps. When this sub-picometer-per-point data [5] is used to characterize a typical FBG spectral peak, the repeatability of the FBG center is better than the 0.5 pm standard deviation indicated here.

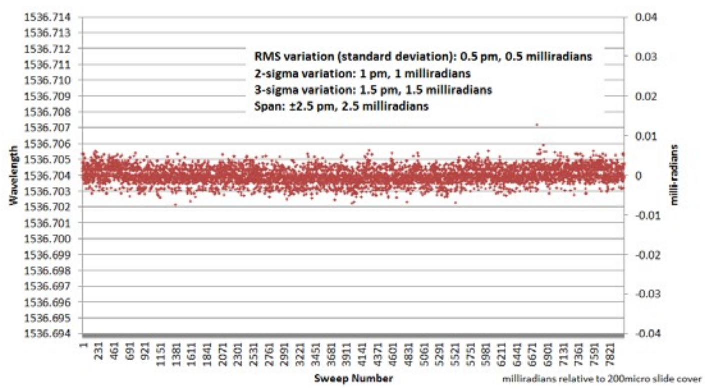

Figure 3. Stability of the laser wavelength referenced to a $H^{13}CN$ gas absorption cell at 100 torr (dBm Optics inc.). Plot shows a total of 8000 laser sweeps over a 30 minute period. Sweep rate was 118 kHz.

In addition to being repeatable from sweep to sweep, the akinetic laser is linear over the entire wavelength range to better than 1pm RMS. This contrasts with the "accordion"-like sweep profile common for mechanically-tuned lasers. This is important to preserve sensor wavelength profile as the sensor moves in wavelength space in response to change in temp, pressure, vibration, etc.

In the experimental test system, the sensor FBGs, which were written using an on-line draw process, had a reflectivity of nominally -30 dB (0.1% reflectivity), and were spaced at 1m intervals along the fiber. Consequently, each sub array has a length of 20m, and the total array length was 1 km.

Figure 4 shows a recorded series of time traces from the array containing 250 FBGs configured in 50 sets of 5 elements. The array was designed to accommodate 20 FBGs in each sub-array, so the experimental system has a capacity for 1000 sensors. Here, the returns from each sub array have been separated and stacked to illustrate the sequential OTDR-type signatures received. The laser was swept over a 60 nm range during the input pulse to the array.

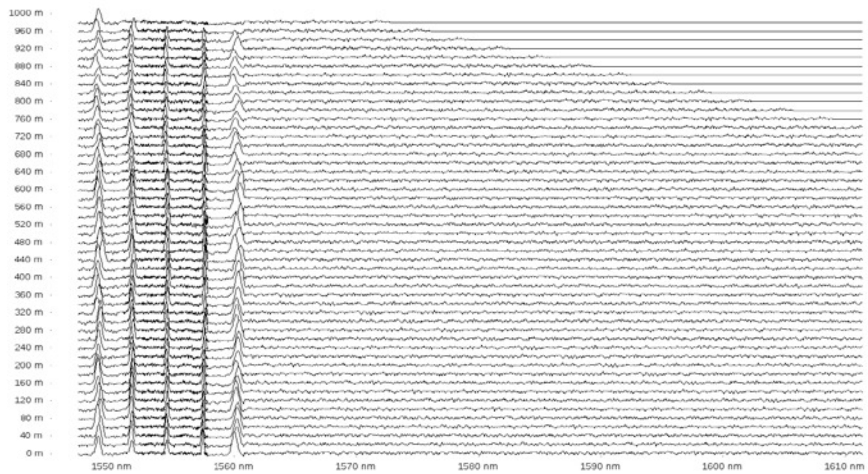

Figure 4. Return signal from the array of 250 FBGS arranged in 50 sub-arrays of 5 FBGs each. The system design would accommodate 20 FBGs in each sub array for a total capacity of 1000 FBGs.

4. DISCUSSION/LIMITATIONS

The limits to this methodology are in the ability to resolve small arrival time differences in the grating reflectometry signatures. With the current incarnation of the swept laser, which runs at a clock rate of 400 MHz, each point represents 2.5 ns of time, and a wavelength step of ~ 20 pm at a sweep rate of 100kHz (for a max wavelength sweep range of 80 nm). For a 'typical FBG profile of ~ 200 pm, the grating return signals are thus characterized by approximately 10 time samples. Standard centroid calculations can readily provide determination of the pulse center timing to better than the a time resolution to give ~ 1 pm effective wavelength resolution. Averaging can produce better detection capability down to ~ 0.1 pm. One limitation in this approach is temperature sensitivity: Temperature changes in the 'lead' fibers, and sub array fibers will affect the optical delay from the source to a given FBG. Consequently, the system is susceptible to temperature-induced measurement errors. This can be a relatively small error, but will be increasingly significant for more distal 'sub-array' FBGs. While this will not impact applications involving dynamic measurands (vibration & acoustic fields), it does impact quasi-static measurands. This effect can be negated, however, by having an 'athermal' grating in each sub array and referencing the subarray FBG readings to these reference grating timings.

5. SUMMARY

We have demonstrated and characterized an akinetic, all-semiconductor swept laser interrogation system. Results include repeatability of < 0.5 pm, yielding temperature sensitivity and strain repeatability of 0.05 °C and 0.5 $\mu\varepsilon$. We demonstrated an array of 250 gratings in a system configuration designed to support over 1000 sensors in a single fiber.

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