Spectral Peak Tracking for Enhanced Fiber Optic Sensing

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ABSTRACT

Within this work, we describe our newly developed interrogation scheme for fiber optic sensing applications. This measurement system will be utilized in Ariane launchers for monitoring temperature and mechanical stress distribution during flight. The acquired sensing data can be used to control propulsion unit an thrusters and thereby adapt the flight path in a way that damage on the launcher is prevented.

In order to detect the peak wavelength of e.g. fiber Bragg grating (FBG) sensors, a tunable laser source based on a modulated-grating laser diode is able to scan through a more than $40nm$ wide spectrum in the infrared region. Several sensors with different spectral answers can be placed inside one sensor fiber and then interrogated sequentially. The magnitudes of the reflected intensities depend on the actual sensor position that is determined by the measurand (e.g. temperature). One single sensor is scanned by a variable number of spectral sampling points and the spectral answer of the sensor is then calculated by centroid algorithms. Depending an the spectral width of one sensor, the number of sensors that shall be interrogated and the required sampling points per sensor, a maximum sampling frequency of $240kHz$ is achievable with our hardware.

Contrary to comparable systems, our interrogator is capable of switching to any available wavelength of its spectrum within a couple of nanoseconds. Therefore standard continuous sweeping through the entire spectrum is not necessary. This results in a new measurement scheme, wherein spectral gaps between consecutive sensors do not need to be scanned and can be skipped. Since most of the spectrum consists of the gaps between the sensors, overall measurement time is thereby reduced significantly. One problem arises from this measurement scheme: Due to the fact that the sensor's spectral answers vary in time, a special algorithm for tracking the spectral movement has to be implemented.

The scope of this work is the description, implementation and assessment of this new peak tracking procedure. After describing the measurement setup, we will therefore explain the algorithm behind the peak tracking measurement. Afterwards the simulation process is explained and results are shown. Performance obtained by peak tracking compared to standard continuous wavelength scanning is evaluated in detail and further development steps which are necessary to obtain a fully sophisticated interrogation systems are discussed.

Keywords: FBG, fiber optic sensing, sensor peak tracking

1. INTRODUCTION

Fiber optic sensing is on the way towards its utilization for space applications. The advantages of optical sensors like Fiber-Bragg Gratings (FBG) are very desired in space applications. Lightweight, insensitivity to electromagnetic disturbances, ease of distribution and scalability are natural properties of fiber optic sensing that have to be fulfilled anyway by a sensor system working in space environment. The possibility to implement several FBG sensors in one single sensor fiber without influencing each other and to install such fibers in composite materials during their fabrication are also desirable for space systems. Because of these reasons our work is carried out within the framework of the ESA funded project "Structural Monitoring of Ariane Launchers using Fiber Optic Sensing"[1] in cooperation with Kayser-Threde GmbH *.

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Interrogation schemes that are commercially available are based on two different measurement principles. In the first case a broadband light source illuminates the sensor fiber and reflected spectra of different sensors are evaluated by a spectrometer. In the second case a spectrally narrow laser beam, whose wavelength is tuneable, is used to scan through the spectrum of a sensor and reflected intensities are evaluated in order to calculate the spectral answer of the sensor. Measurement setups of both schemes in principle consist of a illumination source on the output side and a light detection source on the input side of the interrogator. The overall complexities of both systems are quite comparable to each others, but inside the interrogators complexity is located at different positions. In the first measurement scheme the illumination output normally is implemented as a simple broadband light source e.g. a superluminescent diode, but the input side is more complicated since the wavelengths need to be determined. In the second measurement scheme the laser source usually includes the complexity since it needs some tuning capability but the intensity measurement is done simply by photo detectors.

2. MEASUREMENT SETUP

Our measurement setup is shown in figure 1. The main requirements on the measurement system that have to be fulfilled are an overall number of three sensor fibers holding a maximum number of eight sensors each. All sensors together have to be read out with a minimum frequency of $10kHz$ and an accuracy in the order of $5pm$.

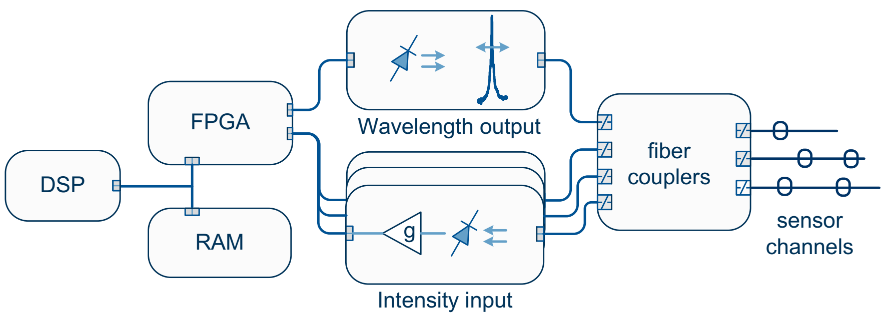

Figure 1. Principle measurement setup of our fiber optic interrogation system. The three control currents of the tunable laser diode are provide by three DAC devices. The laser output pulses are guided to the sensors which are mounted in up to three sensor fibers. The reflected intensities are measured by photo amplifiers and digitized by three ADC devices. All DAC and ADC devices are controlled by the FPGA, measured data is transferred from FPGA to DSP for centroid calculation. The RAM holds all available laser wavelengths as LUT.

The core of our interrogation system is a modulated-grating laser diode. Since this laser diode is a monolithic device and our interrogator does not have any free beam optics, the measurement setup is insensitive to shock and vibration loads. Contrary to other laser diodes, a modulated-grating laser diode is constructed as Y-geometry.[2] The nontransparent reflector of the diode's cavity is split into to arms, in each arm an optical grating is responsible for light reflection. The output wavelength of the laser-diode can be adjusted electronically by feeding in two analog currents I_{R1}, I_{R2} into the two grating structures. The injected charge carriers result in a variation of reflected wavelength. A third current I_{Ph} is injected into a common area for phase adjustment.[3] The output wavelength can not be adjusted continuously due to the principle of the modulated-grating wavelength generation. Therefore only discrete wavelengths, which are not spectrally equidistant distributed can be adjusted by the three input currents.

In order to provide the control currents of the laser diode, our system uses three digital to analog converters (DAC) with a sample rate of $50MS/s$. Since the characteristic curves of the current inputs are not linear,[3] the interrogation systems needs to be characterized with the DAC output voltages. The characterization results in a matrix (see figure 2) comprised of four columns (λ, I_{R1}, I_{R2} and I_{Ph}), where not the currents but the corresponding DAC values are placed in the matrix rows. This wavelength-sorted matrix is used as "look-up table" (LUT) in order to determine the required current triplet for a desired output wavelength during the measurement process. Considering a mean spectral distance of approximately $4pm$ results in a LUT that has approximately 10000 entries (rows). As it will be explained later, the LUT is saved in an addressable memory and fast access to the required DAC data is achieved by address pointers.

n	λ	I_{R1}	I_{R2}	I_{Ph}
1	λ_1	$I_{R1,1}$	$I_{R2,1}$	$I_{Ph,1}$
2	λ_2	$I_{R1,2}$	$I_{R2,2}$	$I_{Ph,2}$
3	λ_3	$I_{R1,3}$	$I_{R2,3}$	$I_{Ph,3}$

⋮

Figure 2. The LUT holds all values that can be provided to the DAC devices in order to generate a dedicated wavelength.

On the input side of our interrogator, three fast photo detectors combined with transimpedance amplifiers are used to measure the input intensities. Since the input data needs to be processed in order to receive the spectral answer, the analog output of the amplifiers needs to be digitized. This is done by analog to digital converters (ADC) having a maximum sample rate of $25MS/s$.

All of the DAC and ADC devices together need an overall number of 128 bit for input control (DAC devices) or data acquisition output (ADC devices). This is achieved using a field programmable gate array (FPGA) that is capable of providing all output data and pick up all input data in parallel. A digital signal processor (DSP) is connected to the FPGA serially because a DSP is perfectly suited for calculation of the centroid algorithm. If signal filtering (e.g. low-pass filtering) or averaging is required, this can additionally be implemented inside the DSP.

The choice of the above described components and subsystems of our interrogator results in a very flexible and adaptable system. The main advantage is, due to the wavelength switching capability, that the readout frequency of every single sensor can be adjusted in a wide range. Since, as stated earlier, 24 sensors can be read out with a frequency of $10kHz$ or one single sensor could be read out with a maximum frequency of $240kHz$. Achieving different sample rates for different sensors could for example be used to sample critical sensors used for structural monitoring more often than uncritical temperature sensors.

3. MEASUREMENT PRINCIPLE

This section gives a short overview of how FBG sensors are interrogated by our tuneable laser system. Firstly we will show the sampling principle in the wavelength domain, secondly the according time domain view is explained.

3.1. Wavelength Domain

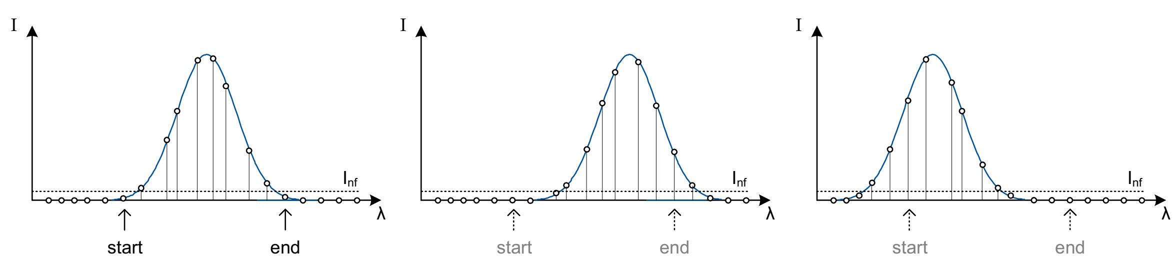

Figure 3. One FBG is sampled by a variable number of sampling wavelengths. Due to a measurand change, the sensor answer is spectrally moving to higher or lower Wavelength depending on the gradient of the measurand change.

Figure 3 shows one FBG sensor that is sampled by several different wavelengths. λ_{start} respectively λ_{end} indicate wavelengths at left respectively right end of the sensor's spectral answer that have a intensity lower than the defined noise floor level I_{nf}. These two wavelengths will later be used for peak tracking.

In order to determine the mean wavelength of the sensor, all ten wavelength pulses need to be generated by the laser diode and have to be guided to the sensor. The reflected intensities can be measured at the related photo detectors after the traveling time (time of flight ToF) of the pulse.[4] Subsequently the measured intensities are transferred to the DSP where the mean wavelength is calculated by an enhanced centroid algorithm.[3] As soon as the measurand changes, the spectral response of the FBG is shifted to lower or higher wavelengths depending on the gradient of the measurand change. Now the interrogator "follows" the movement, otherwise the spectral answer is lost.

3.2. Time Domain

In the time domain picture (figure 4) all ten sampling wavelengths are sequentially generated by the laser diode. Each sampling wavelength of the sensor has the same ToF because the ToF is only dependent on the distance between the senor and the interrogator.[4] This results in a time delay between sending and receiving a laser pulse equal to the ToF and common to all laser pulses of the same sensor. The varying reflected intensity values indicate the spectral position of the wavelengths within the FBG (compare to figure 3).

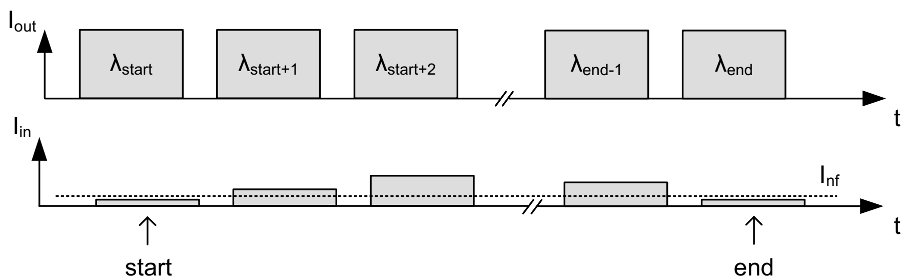

Figure 4. In the time domain, the laser diode transmits a sequence of laser pulses with increasing (or decreasing, depending on the case) wavelength.

4. PEAK TRACKING PROCEDURE

A sensor fiber including a maximum of eight different sensors with a bandwidth of $400pm$ each yields a "spectral loading" of $3.2nm$. Since the full spectrum of the laser diode comprises more than $40nm$ roughly 90 % of the entire spectrum is unused and can be skipped during the measurements all the time. In order not to loose the spectral answers of the sensors, their variation has to be tracked so that the sampling wavelengths can exactly be attained. The peak tracking algorithm is explained in this section considering only one single FBG for the sake of simplicity.

As shown in figure 3 λ_{start} and λ_{end} are the two wavelengths beside the spectral answer of a FBG that have zero reflected intensity. Since there is always some noise floor level I_{nf}, zero intensity in that case means a reflected intensity having a value less than I_{nf}: $I_{refl}(\lambda_{start}) < I_{nf}$ correspondingly $I_{refl}(\lambda_{end}) < I_{nf}$. By scanning through the entire output spectrum of the laser diode as an initial step, these two wavelengths can be determined. After the measurement has started and the spectral answer of the FBG moves due to alteration of the measurand, the reflected intensities between $I_{refl}(\lambda_{start})$ and $I_{refl}(\lambda_{end})$ are evaluated for the determination of the mean wavelength. The movement of the spectral answer peak is tracked by additionally observing the two wavelengths $I_{refl}(\lambda_{start})$ and $I_{refl}(\lambda_{end})$.

4.1. Measurement Case Selection

Time that passes between two consecutive measurements of one FBG sensor depends on the overall sampling rate. Considering the two extreme cases of only one single sensor and the maximum number of 24 sensors, a time delay T_d of approximately $4\mu s < T_d < 100\mu s$ is possible. Due to the gradient of the measurand change, the following cases concerning the movement of the sensor's spectral answer can occur:

1st Case: No movement

If the measurand change is very slow or even zero, the spectral peak does not move as far as the distance between two sampling points. This case is indicated by the condition:

$$I_{refl}(\lambda_{start}) < I_{nf} \wedge I_{refl}(\lambda_{end}) < I_{nf} \tag{1}$$

In that simple case no further peak tracking procedure is necessary and all wavelengths between λ_{start} and λ_{end} are sampled in order to recalculate the mean wavelength.

Special attention is payed to the mean wavelength calculation performed by the DSP. Furthermore, the gradient of the measurand change may be so high, that it is shifted completely out of the spectral region which is spanned by λ_{start} and λ_{end}. Detection of this error-case is easy, only the measured intensities have to be checked whether they are lower than I_{nf}.

2nd Case: Movement to higher wavelengths

If the measurand changes in a way that the spectral peak shifts to higher wavelengths, the condition for the second case is:

$$I_{refl}(\lambda_{start}) < I_{nf} \wedge I_{refl}(\lambda_{end}) > I_{nf} \tag{2}$$

Because $I_{refl}(\lambda_{start})$ does no longer belong to the spectral answer of the sensor, this case can only be handled by sampling around $I_{refl}(\lambda_{end})$. Firstly, sampling starts towards higher wavelengths until a wavelength with an intensity less than I_{nf} is detected. This wavelength becomes the new end wavelength $I_{refl}(\lambda_{end,new})$ when the peak tracking procedure is started the next time for this sensor. After $I_{refl}(\lambda_{end,new})$ has been found, sampling starts again from $I_{refl}(\lambda_{start})$, but this time towards lower wavelengths. The first wavelength which has a reflected intensity of less than I_{nf} becomes the new start wavelength $I_{refl}(\lambda_{start,new})$.

3rd Case: Movement to lower wavelengths

If the measurand changes in a way that the spectral peak shifts to lower wavelengths, the condition for the third case is:

$$I_{refl}(\lambda_{start}) > I_{nf} \wedge I_{refl}(\lambda_{end}) < I_{nf} \tag{3}$$

Because $I_{refl}(\lambda_{end})$ does no longer belong to the spectral answer of the sensor in this case, it has to be sampled around $I_{refl}(\lambda_{start})$. The rest of the procedure corresponds to the second case.

4th Case: Movement to lower wavelenghts

The fourth case theoretically is not possible. However, if e.g. the noise level is not set to a proper value, the following condition might occur:

$$I_{refl}(\lambda_{start}) > I_{nf} \wedge I_{refl}(\lambda_{end}) > I_{nf} \tag{4}$$

This would indicate a peak that is spectrally broader than the last time it was measured. Handling this case is just the same procedure as in second or third case.

4.2. Peak tracking algorithm

The above described measurement cases are handled automatically by our peak tracking algorithm shown in 5 which is executed inside the FPGA. For this algorithm it is assumed that all wavelengths are saved in an addressable memory (a RAM memory in our system) as an assorted LUT. One single wavelength intensity measurement is encapsulated in a function "Measure-Intensity" which requires one parameter value and returns the measured intensity. The parameter value n is the RAM address of the wavelength which shall be emitted by the laser diode. "Measure-Intensity" in principle executes four successive operational steps:

1. Get required control current triplet from address n

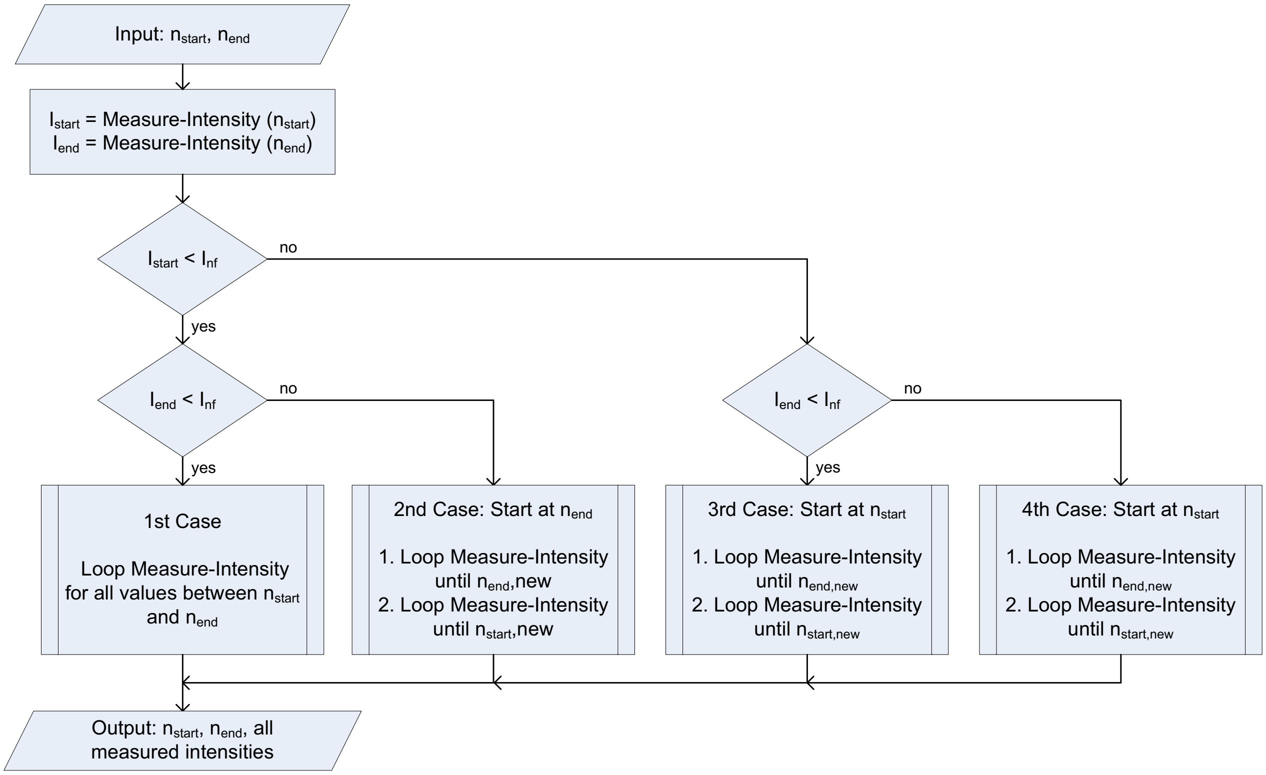

Figure 5. This program flow diagram shows the different cases in the peak tracking algorithm. Depending on the measured intensity values of $I_{refl}(\lambda_{start})$ and $I_{refl}(\lambda_{end})$, the sensor answer is tracked towards higher or lower wavelengths.

2. Generate laser output pulse using control current values as DAC inputs
3. Wait for ToF until reflected intensity arrives at photo detector input[4]
4. Read and return ADC intensity value

At the beginning of the measurement, both addresses n_{start} and n_{end} which correspond to the initial wavelengths λ_{start} and λ_{end} are handed over to the algorithm by the DSP. After the intensities at both wavelengths have been measured, the algorithm selects the measurement case dependent on the two intensities. After the new start and end addresses $n_{start,new}$ and $n_{end,new}$ have been determined and all wavelengths in between have been sampled, $n_{start,new}$, $n_{end,new}$ as well as all measured intensities are returned to the DSP. Storing the new addresses and evaluating the mean wavelength of the sensor answer can then be conducted by the DSP independently from FPGA operations. At the next measurement of the same sensor the stored addresses are handed over to the FPGA again.

4.3. Limitations of the peak tracking procedure

Depending on the time delay T_d between two consecutive measurements of one sensor, only a maximum gradient Δ_{max} of the measurand change is allowed. If the measurand change is able to show an absolute gradient higher than Δ_{max}, correct function of the interrogation system is not assured, since the sensor answer peak may be lost. Assuming a FBG sensor with a spectral bandwidth of $400pm$, our interrogation setup will work properly if the gradient satisfies the condition $\Delta_{max} < 4\frac{pm}{\mu s}$ for a fully loaded system with a number of 24 sensors and $\Delta_{max} < 100\frac{pm}{\mu s}$ for a system holding only one sensor. These values correspond to measurand change gradients

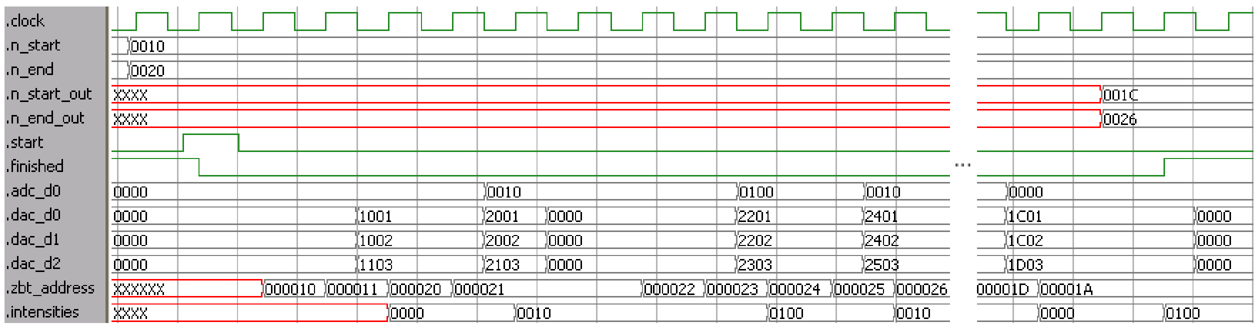

Figure 6. This timing diagram shows the results of our peak tracking simulation of a sensor answer that was moving towards higher wavelengths. $n_{start,new}$ and $n_{end,new}$ are RAM addresses of the DAC values which are needed to generate output wavelengths of λ_{start} and λ_{end}. "adc_d0" is the signal coming from the input ADC device. The DAC values are encoded as described in the text. Since the used RAM only has a data width of 32 bit, always two memory lines are used for storing all three 16 bit DAC values.

of approximately $0.3\frac{°C}{\mu s} < \Delta_{max} < 7.3\frac{°C}{\mu s}$ for a temperature sensor and $3.3\frac{\mu\varepsilon}{\mu s} < \Delta_{max,\mu\varepsilon} < 83.3\frac{\mu\varepsilon}{\mu s}$ for a strain sensor.[5]

5. SIMULATIONS

In order to simulate the peak tracking algorithm only the in- and output signals of the FPGA have to be simulated since the algorithm is designed such that it can be executed completely inside the FPGA. As described earlier, the FPGA controls all data flow to DAC inputs and from ADC outputs. During simulations DSP, RAM and all digital in- and output ports to the DAC and ADC devices are simulated. This is done by means of a testbench design which is standard in FPGA simulations. In order to enable a simple evaluation of the simulation results, not real DAC values are provided inside the simulated RAM. Instead, 16 bit data that are encoded in a way that the value itself allows an obvious determination of RAM address and respective DAC channel: The first byte determines the row of the LUT, the second byte represent I_{R1}, I_{R2} or I_{Ph} as numbers 1, 2 or 3 respectively. The noise level I_{nf} is set to zero during simulations. Figure 6 shows the simulation results of a second case measurement scenario.

6. EVALUATION OF RESULTS

Simulating all different cases (second case is shown in figure 6) indicated a behavior of the peak tracking algorithm as it was expected. As long as the measurand does not change faster than the calculated values (see chapter 4.3), a sensor answer can be tracked by the algorithm. If the sensor answer is lost, a new initialization phase has to be conducted in order to find the values for start and end wavelengths. Depending on the sampling resolution, which in our case is determined by the spectral gaps between two consecutive sampling points, the peak wavelength can be determined with more or less accuracy. This additionally results in a variability of our measurement system.

7. CONCLUSION

Within this article we described our work on the field fiber optic sensing based on tunable laser sources. In particular we explained how our interrogation system is built up and how we enhance measurement performance by our newly developed peak tracking algorithm. After detailed explanation of the algorithm itself, we showed and described simulation results.

In combination with ToF tracking[4] our measurement concept results in a variable and practical fiber optic interrogator. The great advantage of peak tracking is the fact that not the entire output spectrum of the tunable laser diode has to be scanned but only the spectral regions were the answers of the implemented sensors are. This results in a significant reduction of measurement time which in turn results in a higher overall read out frequency.

Acknowledgments

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