Performance analysis of interrogators for Fiber Bragg Grating sensors based on arrayed waveguide gratings

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ABSTRACT

Fiber Bragg grating (FBG) sensors have proven to be adaptable for monitoring various physical quantitites like temperature, strain, or even vibrations and acoustic noise. Several interrogation methods, like spectroscopic evaluation, interferometric interrogation, active scanning or active filtering systems or passive filtering systems are capable of monitoring the wavelengths of the FBG sensors. Among the passive filtering systems, interrogators based on arrayed waveguide gratings (AWG) have shown to be promising candidates for sensing with FBGs, especially for high-frequency measurement tasks.

Whereas the resolution- and the accuracy-dependency on light intensity of direct wavelength determining systems like spectrometers or scanning filter systems can be minimized by data processing algorithms, the performance of passive filtering based interrogators is more sensitive regarding uncertainties induced by electrical amplifier noise, FBG peak shape, light source intensity, etc.. The influence of different sources of uncertainties for AWG-based interrogators on the accuracy of the wavelength determination are investigated by an analytical model. The model is evaluated by a numerical simulation. It is shown how strongly the accuracy and the resolution of such an interrogator depend on the mentioned sources of uncertainties. Considering the obtained results, one can say that FBG interrogators based on arrayed waveguide gratings have, including the shown restrictions, the potential for rugged, compact and cost effective high accuracy wavelength interrogators.

Keywords: Fiber Bragg grating, FBG, arrayed waveguide grating, interrogator

1. INTRODUCTION

Fiber Bragg Grating offer a enormous potential for sensing applications, especially for applications where a high degree of multiplexing is required, where convential sensors cannot be used due to to electromagnetical interference or where light weight of the sensor is required. Fiber Bragg gratings transform a physical quantity like temperature or strain into a reflected optical wavelength. As light can propagate through singlemode fibers with only very low attenuation, the sensor can be placed several kilometers away from the interrogation unit. Depending on the sensing application, different interrogating principles are applicable, as there are spectroscopic, interferometric, scanning laser based or intensity based interrogators. For high frequency measuring applications, most of these sensing principles lack from an anti aliasing capability. Intensity based interrogators show as the only of the above mentioned devices the ability to sufficiently suppress signal frequencies above the Nyquist frequency, thus allowing proper implementation of anti aliasing based measurement of FBG sensor wavelengths.

2. FIBER BRAGG GRATING SENSING

2.1. Fiber Bragg Gratings

Fiber Bragg gratings are formed by a periodic modulation of the refractive index inside the core of a singlemode waveguide. This periodicity forms a Bragg Reflector, which reflects light within a certain wavelength band, whereas the rest of the light spectrum is unaffected by the Bragg Grating. The periodic modulation of the refractive index within the core of a singlemode fiber is depicted in figure 1.

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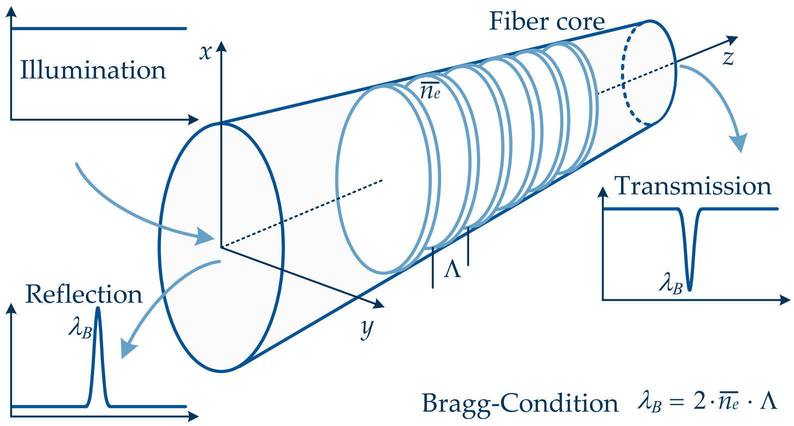

Figure 1. Schematic of fiber bragg grating; depending on the effective refractive index n_{eff} and the refractive index moduation period Λ a specific wavelength is reflected at the fiber Bragg grating

The reflected wavelength is given by[1]

$$\lambda_b \;=\; 2\Lambda \cdot n_{eff} \tag{1}$$

where Λ is the period of the refractive index modulation and n_{eff} is the effective refractiv index of the waveguide core at the Bragg grating. The reflection spectrum of a fiber Bragg grating can be calculated using coupled mode theory. Depending on the apodization of the refractive index profile in the sensor, FBGs exhibit different reflection spectra. In the unapodized case, FBGs show a *sinc*-like reflection spectrum. In this work, the envelope of the reflection spectrum of the FBGs will be considered to be of Gaussian shape, which is a good first order approximation for FBG spectra. Depending on the load and the temperature acting on the Fiber Bragg sensor, the peak wavelength shift is given by[1]

$$d\lambda_B(T,\epsilon_i) = \left[2\Lambda\frac{\partial n_{eff}}{\partial T} + 2n_{eff}\frac{\partial \Lambda}{\partial T}\right] + \left[2\Lambda\frac{\partial n_{eff}}{\partial \epsilon_i} + 2n_{eff}\frac{\partial \Lambda}{\partial \varepsilon_i}\right] \tag{2}$$

where T is the temperature of the sensor and ϵ_i is the i-th component of the strain-tensor at the position of the Fiber Bragg Grating. For temperature sensing applications, this yields a sensitivity of 1° C / 13.7 pm. For strain measurement applications, the sensitivity is given as approximately 1.4 pm / $\mu\varepsilon$.[1]

Fiber Bragg gratings are evaluated by measuring the reflected peak wavelength of each sensor. Using equation 1, the physical quantites to be evaluated can be determined.

2.2. Wavelength division multiplexing (WDM)

As each Fiber Bragg Grating within one optical fiber is reflecting one certain wavelength within the optical spectrum, a plurality of Fiber Bragg Grating sensors can be multiplexed serially, wherein each sensor is operating at a certain wavelength band. The different reflected wavelengths, each of which is associated with a certain FBG, can be interpreted separately.

3. INTERROGATORS BASED ON ARRAYED WAVEGUIDE GRATINGS

3.1. Arrayed waveguide gratings

Arrayed waveguide gratings (AWG) are integrated optical dispersive elements, which are used for dense wavelength division multiplexing (DWDM) applications in optical telecommunication. An AWG, as it is considered in this paper consists of one input port and N output ports. The light incident at the optical input of the device is, depending on the wavelength, mapped onto a specific output port of the AWG. Each output port has a specific transmission profile over wavelength. Conventional AWGs exhibit a Gaussian-like passband shape. In this work, the passband is assumed to be strict Gaussian, whereas real AWGs exhibit a bias transmittance, or overall crosstalk, over the whole spectrum of about -30 ... -45 dB.[2]

3.1.1. Arrayed waveguide based interrogators for FBGs

AWGs can be used as compact and fast wavelength interrogators for fiber bragg gratings.

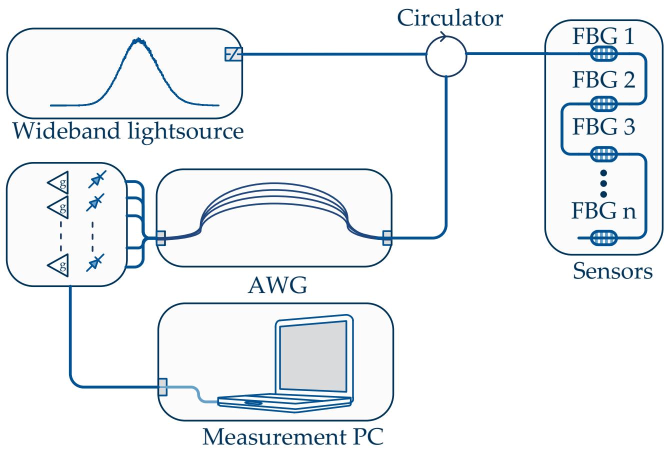

Figure 2. Setup of an AWG-Interrogator comprising a broadband ligtsource (SLD or ASE), an optical circulator, a fiber Bragg grating sensor array, an arrayed waveguide grating, amplifier electronics and a measurement computer

Figure 2 shows a typical setup of an AWG-based interrogator for Fiber Bragg gratings. A broadband lightsource emits light into a singlemode fiber with inscribed fiber Bragg Grating sensors. Each sensor reflects light of a specific wavelength, which is propagating towards the detector unit, comprising the AWG and the detector electronics.

The FBG center wavelength is chosen in a way that the reflected light is spectrally located in between two output channels of the AWG. The spectral location of the reflected light of the FBG and the passband shapes of the output channels are shown in figure 3. The FBG reflection gives rise to light intensity in both adjacent output channels. Considering only one FBG, the intensity in the i-th channel is given by

$$I_i = \int_{-\infty}^{+\infty} T_i(\lambda) \cdot R_{FBG}(\lambda) \cdot L(\lambda) d\lambda \tag{3}$$

where $T_i(\lambda)$ is the wavelength-dependent transmission of the $i-$th AWG output channel, $R_{FBG}(\lambda)$ is the reflection spectrum of the FBG and $L(\lambda)$ is the light source spectral intensity distribution comprising further sources of attenuation in the optical path . The ratio of the light intensity in two adjacent channels i and $i+1$ is a measure for the center wavelength of the refelction peak of the FBG sensor. Sano et. al[3] proposed the logarithmic ratio

$$\rho = log(\frac{I_i}{I_{i+1}}) \tag{4}$$

as an evaluation function for ease of linear signal processing. In this work, for ease of analysis and without restrictions, we choose the ratio

$$\rho = \frac{I_i}{I_{i+1}} \tag{5}$$

as evaluation function for the determination of the sensor Bragg wavelength. For measurement ranges that are not restricted by the detector circuit noise, as well be shown in the following section, ρ is a bijective interrogation function.

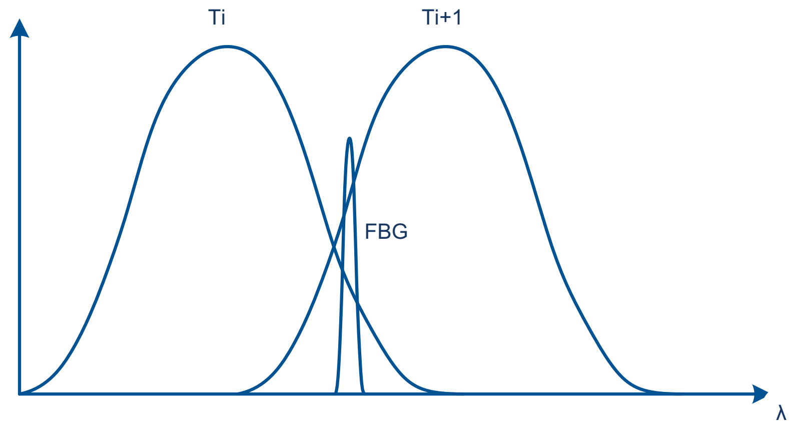

Figure 3. Filter edges formed by slopes of adjacent arrayed waveguide grating output channels T_i and T_{i+1}; spectral location of fiber Bragg grating sensor to be evaluated depicted by narrowband spectral peak

4. PERFORMANCE OF AWG BASED INTERROGATORS

The accurarcy of interrogation methods like spectrometers or scanning laser interrogators is on the one hand depending on the signal quality, e.g. the light intensity, at the detecting element. On the other hand, as the spectral response of the Fiber Bragg Grating sensors is sampled discretely in spectrum, those interrogation methods can make use of wavelength determining algorithms like a center of gravity algorithm, Gaussian fit algorithms or LPO (Linear Phase Operator) algorithms[4,5] .

In contrary, using an AWG interrogator, the light intensity values obtained from intensity measurement in the i-th and the $i+1$-th channel are a direct measure for the wavelength of the FBG sensor. The accuracy therefore is determined by the noise in the electronic detection circuit. Using a simplified amplifier electronics stage with a output noise model considering only the main noise sources, numerical results for the resolution capabilities of an AWG based interrogator are shown in the next section.

4.1. Noise sources

In the most simple case, the light intensities in the output channels of the AWG are picked up by photodiodes and converted into corresponding photocurrents.

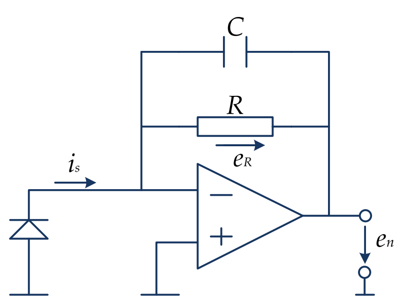

Figure 4. Simplified amplifier circuit, noise sources indicated by i_s and e_R

The current signal is then being amplified using a single stage transimpedance amplifier, as it is shown in figure 4. The output noise voltage of the detecting circuit is depending on a variety of noise sources, as there are the photodetector Shot noise, the photodetector internal resistor thermal noise, the OpAmp input current noise, the OpAmp output voltage noise and the thermal noise of the feedback resistor R. The OpAmp input current noise and the OpAmp output voltage noise are dependent on the chosen OpAmp. By selection of appropriate amplifier ICs, these contributions can be minimized to a negelctable level, compared to the following noise sources. Therefore, only the photodetector Shot noise and the thermal noise of the feddback resistor R are considered to give a fundamental overview of the measurement restrictions for interrogators based on AWGs. The photodetector's internal resistance thermal noise is neglected due to the high inherent value of the internal resistance. Thus, the minimum noise contribution of the signal of the $i-$th output channel is given by

$$e_{out} = \sqrt{4k_B \cdot T \cdot R \cdot B + 2R^2 \cdot e \cdot i \cdot B} \tag{6}$$

where k_B is the Boltzmann-constant, T is the absolute feedback resistor temperature, B is the elctronic bandwidth of the system, R is the value of the feedback resistor and i is the photocurrent generated in the photodiode.

4.2. Analytical model

The sensor Bragg wavelength is determined by evaluating the inverse of the evalutation function

$$\lambda = \rho^{-1}(U_1, U_2), \tag{7}$$

where U_1 and U_2 are the output voltages of the amplifier electronics. The influence of the above mentioned noise sources leads to a uncertainty in the determination of the sensor wavelength of[6]

$$\Delta\lambda = \sqrt{\sum \left(\frac{\partial \rho^{-1}(\lambda)}{\partial U_i}\right)^2 \Delta U_i^2} \tag{8}$$

where U_i is the output volage of the transimpedance amplifier for the $i-$th AWG output channel. Using equation 5, this leads to a wavelength uncertainty of

$$\Delta\lambda = \frac{1}{\frac{\partial \rho(\lambda)}{\partial \lambda}} \cdot \sqrt{\Delta U_1^2 + \Delta U_2^2} \tag{9}$$

where ΔU_1 is the total voltage noise contribtion of channel 1 and ΔU_2 is the total noise contribution of channel 2, respectively.

From eq. 9 it is obvious that the wavelength measurement uncertainty will increase for sensor wavelength with a low value for the channel responce curve, e.g. for wavelengths far away from the channel center.

4.3. Numerical simulations and results

Depending on the Fiber Bragg Grating sensor, the AWG, the light source, etc. used, different measurement accuracies can be achieved. For determining in the influence of the above mentioned quantities on the excpected measurement accuracy, an ideal Arrayed Waveguide Grating with a channel spacing of 200 GHz was simulated numerically.

For measurement purposes, a measurement uncertainty of 10 pm was idenified to be useful for most measurement applications. In the simulated wavelength range of about 1550 nm, 10 pm uncertainty in the wavelength determination yield an uncertainty in a temperature measurement application of about 0.7° Celsius or 7.1 $\mu\varepsilon$.[1]

4.3.1. Resolution dependency on light source intensity

The light source intensity directly influences the performance of the interrogator system. A system with an AWG with 200 GHz (≙2.6 nm) output channel spacing. was used for the simulation. The width (FWHM) of the Fiber Bragg Grating was chosen to be 0.1 nm, which is a reasonable value for draw tower gratings. The FBG exhibtis a peak reflectivity of 30 % at a Gaussian shape of the spectral response of the sensor. In addition, another -10 dB light intensity attenuation was included, comprising losses at the circulator and insertion loss at the AWG.

Figure 5 shows the dependency of the useable measurment range on the light source intensity for light source intensities in the range of 1 μW/nm to 1 mW/nm, which covers ligth sources like superluminescent diodes (SLD) and amplified spontaneous emission (ASE) sources.

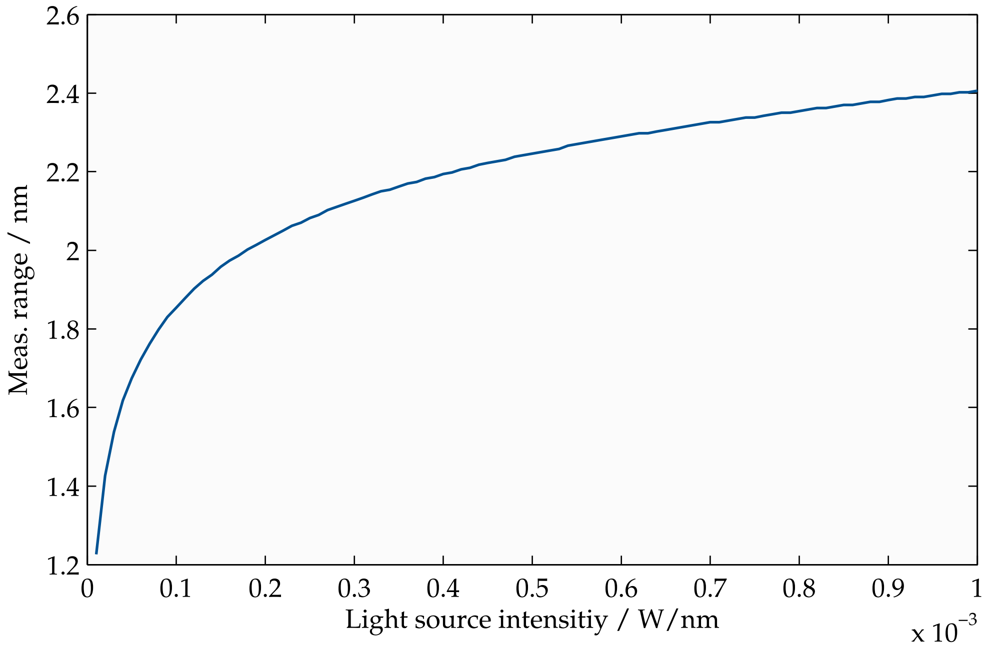

Figure 5. Measurement range vs. light source intensity; useable measurement range indicated by measurement accuracy $\leq$ 10 pm

4.3.2. Dependency on FBG spectral width

Depending on the spectral width of the Fiber Bragg Grating sensor, the light intensity at the detectors grows with increasing width, as can be seen from equation 3. For the same setup as in the previous section, the measurement range for a light source intensity of 200 μW/nm is simulated, whereas the width of the FBG is varied from 0.01 nm to 0.3 nm.

The influence of the FBG spectral width is shown in figure 6. As expected, the measurement range dependency on the FBG width is similar to the dependency on the lightsource intensity.

4.3.3. Dependency on system bandwidth

Both noise sources, e.g. the shot noise of the hotodiode and the feedback resistor's thermal noise, show a white noise behaviour. This means that the noise current is equally distributed over frequency. Thus, the effective noise voltage at the output of the detector electronics circuit is strongly dependent on the bandwidth of the amplifier circuit. According to equation 9 and equation 6, the electronics bandwidth both influences the photodiode's Shot noise contribution to the overall noise, as well as the thermal noise contribution of the electronics feedback resistor.

Therefore, as can be seen in figure 7, the acceptable measurement range is strongly dependent on the system bandwidth. The loss in useable measurement range with increasing system bandwidth can be compensated by choosing FBG sensors with larger spectral width or increasing the light source spectral intensity.

4.3.4. Dependency on AWG channel width

The light intensity at the photodetectors is dependent on the transmission value of the AWG output channel spectra. Lowering the slope of the edges of the AWG channels leads, on the one hand, to a lower sensitivity of the system, whereas on the other hand, it leads to higher power in the ouput channels, which leads to a better SNR. For conventional AWGs, the slope of the output channels, respectively the width of the output channels can be tuned to some extent. Figure 8 shows the useable measuremnt range for an AWG with 200 GHz channel

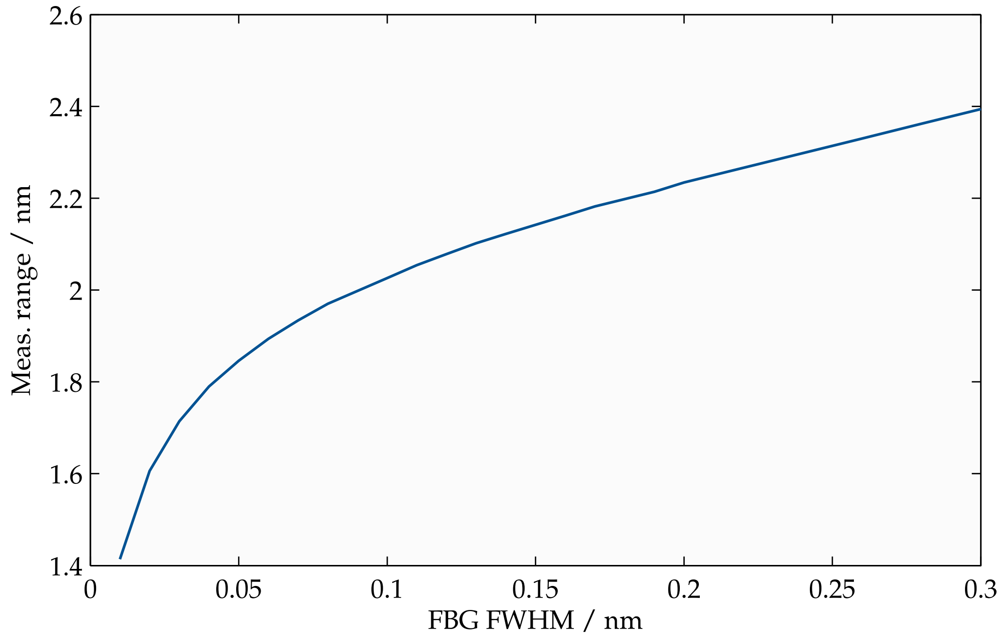

Figure 6. Measurement range vs. FBG FWHM for Gaussian shaped fiber Bragg grating sensor; useable measurement range indicated by measurement accuracy $\leq$ 10 pm

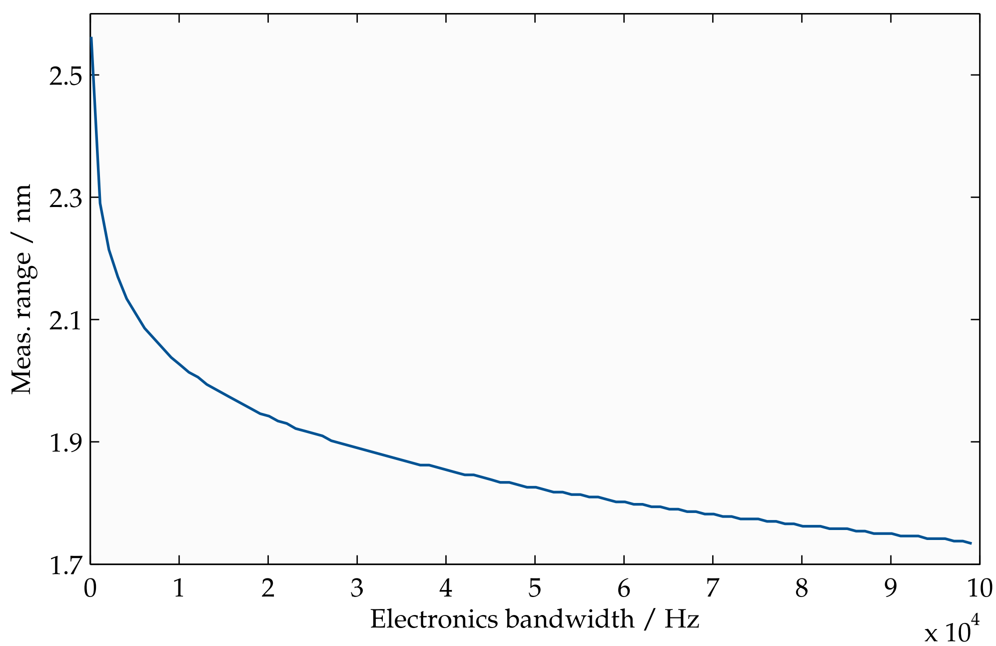

Figure 7. Measurement range vs. electronics bandwidth; noise conributions are bandwidth-restricted by lowpass filter; useable measurement range indicated by measurement accuracy $\leq$ 10 pm

spacing, a FBG width of 0.1 nm, a light source intensity of 200 μW/nm and a feedback resistor value of 10 MΩ. The FWHM of the AWG output channels is varied from 1 nm to 1.8 nm at a channel spacing of 2.6 nm.

The system shows a linear relation between the spectral channel width and the useable measurement range. It

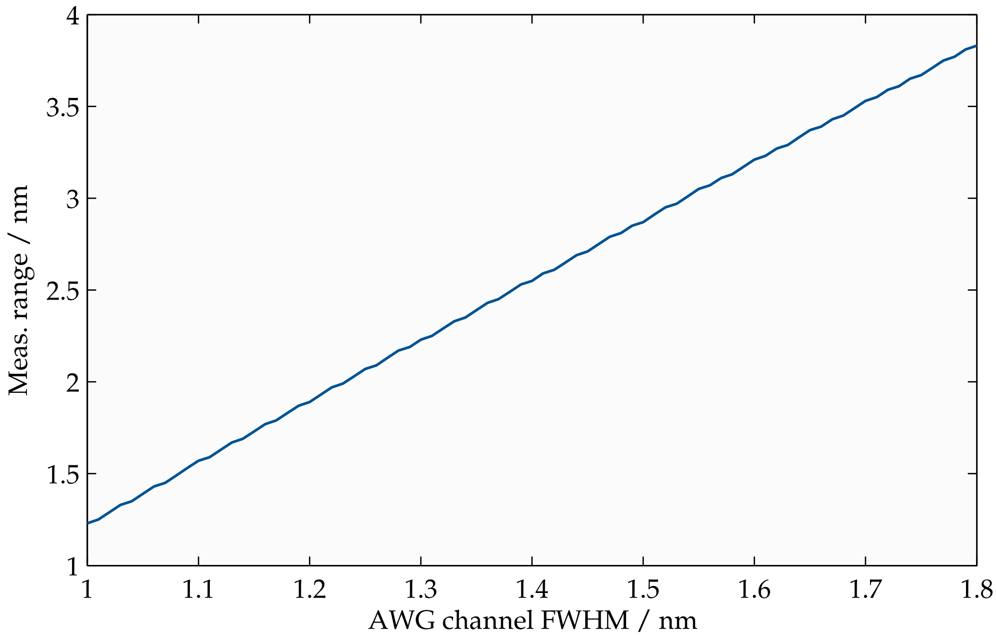

Figure 8. Useable measurement range vs. AWG output channel width (FWHM) for 2.6 nm channel spacing

has to be considered that for real AWGs the tuneability of AWG output channel width is restricted due to design restrictions.

5. CONCLUSION

It has shown that the useable measurement range of AWG interrogators is strongly dependent on a series of parameters. On the one hand, optical paramters of the Fiber Bragg grating sensors like peak reflection and spectral width of the sensor directly influence the light intensity at the detectors and thus influence the sensor shot noise contribution to the system resolution capabilities, whereas the noise originating from the amplifier feedback resistor is not affected thereof. The choice of the appropriate lightsource affects the resolution capabilities of the system in the same way.

The noise contribution of the detector electronics can be restricted by determination of detector bandwidth. The fundamental noise sources of amplifier electronics have been considered within our simulations. The presented simulated measurement ranges with a measurement uncertainty lower than 10 pm therefore are a lower boundary consideration.

It is shown that the most important contribtion to the useable measurement range is given by the spectral width of the AWG output channels. The measurement range is linearly affected by the channel width. Commercially available AWGs with Gaussian passband shape are designed for DWDM applications, where a high channel separation is achieved by lowering the channel crosstalk, thus lowering the output channel width. Therefore, the useable measurement of FBG interrogators based on commercially available AWGs for DWDM applications is below the maximum achievable values.

Beside the electronic noise contributions, as they are simulated in this work, the measurement uncertainties and thus the useable measurement range is influenced by other parameters like polarization dependence of the AWG channel spectra. Polarization compensation of AWGs has been previously demonstrated,[7] but commercially available AWGs show a polarization dependent loss (PDL) of about 0.2 dB. Furthermore, the output channels shape differs from the assumed Gaussian passband shape, especially for wavelength far away from the center wavelength of the channels.[3]

Arrayed waveguide gratings have already proven their ability for high frequency interrogation of Fiber Bragg

Grating sensors.[8] Depending on the desired measurement resolution, measurement bandwith and sensor bandwidth, the sensors' spectral properties, as well as the light source have to be chosen properly.
A basic step for increasing the performance of AWG interrogators compared to interrogators based on commercially available AWGs is to design an AWG with increased channel passband width.

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