Capacity of Wavelength and Time Division Multiplexing for Quasi-Distributed Measurement Using Fiber Bragg Gratings

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Abstract. *In this paper, an analysis of the use of wavelength and time division multiplexing techniques for quasi-distributed measurement in uniform fiber Bragg gratings is presented. To date, publications have concentrated on the determination of the maximum number of fiber Bragg gratings on one optical fiber using wavelength and time division multiplexing. In this paper, these techniques will be extended to determine the spectral width of wavelength division multiplexing in terms of the spectral width of the light emitting diode, the spectral width of the Bragg gratings, the measurement ranges of the individual sensors, and the guard band between two adjacent Bragg gratings. For time division multiplexing, a description of the time and power conditions are given. In particular the reflected power, first order crosstalk and chromatic dispersion have been considered. Finally, these relationships were applied to verify a design in a simulation using OptiSystem software.*

Keywords

Capacity, fiber Bragg grating, multiplexing, sensor.

1. Introduction

FBGs (Fiber Bragg Gratings) are mostly used for quasi-distributed measurement of deformation and temperature. The most common types of multiplexing are TDM (Time Division Multiplexing) and WDM (Wavelength Division Multiplexing). To determine the required capacity of these multiplexing techniques, certain relationships must be known. For WDM, the important parameters are the spectral width of the LED (Light Emitting Diode) and the spectral width of individual FBGs. The final capacity is given by the ratio of the spectral widths of the LED and one individual FBG. In the case of TDM, knowledge of the time interval between returning impulses from the FBG sensor array is required. The limiting parameter here is the width of the input impulse. This width must be shorter than the time taken for the roundtrip of the light between adjacent FBGs. The capacity of TDM is also influenced by the chromatic dispersion, reflectivity of individual FBGs, crosstalk between channels, Rayleigh scattering, and other attenuation processes in an optical fiber.

Measurement of a large array of FBGs is necessary to realize parameters such as the measuring range, the shape of the LED spectrum, and in the case of WDM the shape of the FBG spectra.

2. Quasi-Distributed Measurement with FBG

2.1. FBG Sensor

A fiber Bragg grating is formed by a periodic change of refractive index in the optical fiber (see Fig. 1). Dependent on the grating period, the light of a specific wavelength called the Bragg wavelength λ_B is reflected, and the other wavelengths are transmitted. The Bragg wavelength is given by:

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where n_{eff} is the effective refractive index of the optical fiber and Λ is the periodic change of the refractive index.

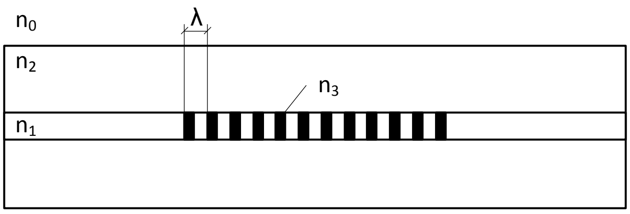


Fig. 1: Structure of fiber Bragg grating.

The Bragg wavelength depends on a spatial period of the refractive index variation. Deformation or temperature acting on the FBG results in a change in the period of the refractive index. The normalized FBG strain response at constant temperature is:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta\varepsilon} = 0.78 \cdot 10^{-6}\mu\text{strain}^{-1}. \tag{2}$$

Normalized temperature sensitivity at constant strain is:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta T} = 6.678 \cdot 10^{-6}\,^{\circ}\text{C}^{-1}, \tag{3}$$

where $\Delta\lambda_B$ is the Bragg wavelength shift, ΔT is temperature change and $\Delta\varepsilon$ is strain change [1].

2.2. WDM and General Capacity

For the multipoint measurement with an FBG, it is necessary to distinguish the resultant signal contributions of individual FBGs. The simplest method is to use WDM as shown in Fig. 2. Light from the LED passes through the circulator to the FBG array, and the reflected light is detected in the OSA (Optical Spectral Analyser), where each FBG is tuned to a different Bragg wavelength. In the OSA, each peak represents one FBG, and the respective frequency shifts are related to the applied deformation or temperature change. The general relation for the capacity of WDM is given by:

$$N = \frac{\text{FWHM}_{\text{LED}}}{\text{FWHM}_{\text{FBG}}}, \tag{4}$$

where FWHM_{LED} is the spectral width at half maximum LED power output, and FWHM_{FBG} is the spectral width at half maximum FBG reflected power [2].

This relationship defines the maximum number of FBGs that can be placed on one optical fiber. However, this is problematic for the measurement of deformation or temperature.

A shift of the Bragg wavelength will cause overlapping of two adjacent FBG spectra making it impossible to distinguish the contribution of individual FBGs.

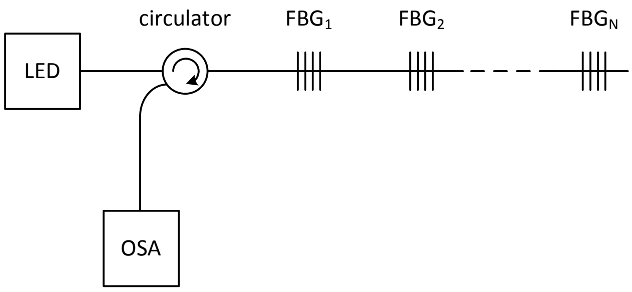


Fig. 2: Scheme of WDM with LED, FBGs and OSA.

2.3. Measurement Range, Measurement Channel and Guard Band

For the most efficient use of the LED spectral width, it is important to define the measurement range for each FBG in the array. For the correct measurement of strain and temperature, it is required that every FBG operates within its measurement range to avoid measurement error caused by the overlapping of adjacent spectra. The measurement range is defined by the minimum and maximum values of temperature or strain to be measured. The measurement channel is shown in Fig. 3 and is dependent on the individual FBG measurement ranges.

Where the measurement channels are close together, an overlap of adjacent spectra can occur. The limiting case is where i^{th} Bragg wavelength is at a maximum value in the measurement range, and $(i+1)^{th}$ Bragg wavelength is at a minimum value in the measurement range. Therefore, it is necessary to introduce a guard band (GB) between adjacent measurement channels.

The size of guard band should be large enough for sufficient resolution between two adjacent spectral peaks. On the other hand, the guard band should be small as possible because of the limited width of the LED spectrum. In the case of a Gaussian spectral

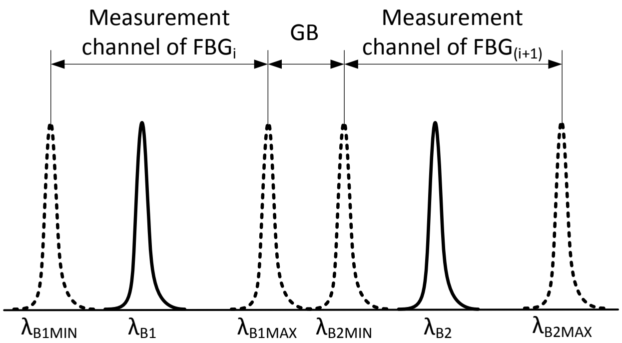
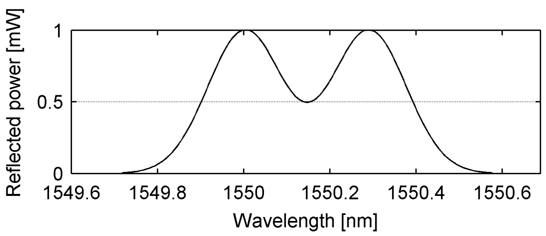
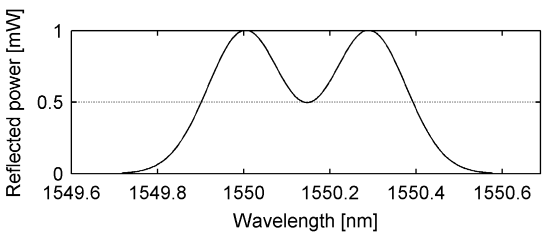


Fig. 3: Measurement channel and guard band.

characteristic as shown in Fig. 4(a), the optimum size of the guard band is such that the two spectral peaks are distinguished by a decrease in power to half of the maximum power (Fig. 4(b)).



(a) Shapes of FBG spectra.



(b) Ideal guard between two adjacent FBGs.

Fig. 4: An analysis of the size of guard band for two adjacent FBGs with a Gaussian shape.

The size of the guard band GB for a Gaussian FBG spectrum is given by:

$$GB = 1.44 \cdot \mathrm{FWHM}_{\mathrm{FBG}}. \tag{5}$$

2.4. Calculation of WDM Capacity

The strain or temperature sensitivity given by Eq. (2) and Eq. (3) is dependent on the Bragg wavelength. Therefore the width of the measurement channel is not only given by the measurement range, but it is also dependent on the Bragg wavelength of each individual measurement channel.

Determination of the WDM capacity for the measurement of strain is explained in the following text. In practice, it is possible to calibrate each FBG measurement channel for the measurement of strain or temperature for any measurement range. First it is necessary to calculate the Bragg wavelength of the first measurement channel such that the Bragg wavelength corresponding to the minimum strain to be measured will be equal to the lower wavelength at the LED FWHM power output, that is:

$$\lambda_{B(1)\,\min} = \lambda_{LED\,\min}. \tag{6}$$

The Bragg wavelength of the first measurement channel is:

$$\lambda_{B(1)} = \frac{\lambda_{B(1)\,\min}}{1 - N_\varepsilon \left|\Delta\varepsilon^-_{(1)}\right|}, \tag{7}$$

where $\lambda_{B(1)\,\min}$ is the minimum wavelength of the first measurement channel, N_ε is the normalized deformation coefficient and $\left|\Delta\varepsilon^-_{(1)}\right|$ is the minimum strain acting on the FBG in absolute value.

The maximum wavelength of the first measurement channel is given by:

$$\lambda_{B(1)\,\max} = \lambda_{B(1)} + N_\varepsilon \cdot \lambda_{B(1)} \cdot \Delta\varepsilon^+_{(1)}, \tag{8}$$

where $\Delta\varepsilon^+_{(1)}$ is the maximum strain acting on the FBG.

The spectral width of the first measurement channel is given by:

$$\Delta_{ch(1)} = \lambda_{B(1)\,\max} - \lambda_{B(1)\,\min}. \tag{9}$$

It is possible to calculate the spectral width of subsequent channels as follows:

$$\lambda_{B(i)\,\min} = \lambda_{B(i-1)\,\max} + GB, \tag{10}$$

$$\lambda_{B(i)} = \frac{\lambda_{B(i)\,\min}}{1 - N_\varepsilon \left|\Delta\varepsilon^-_{(i)}\right|}, \tag{11}$$

$$\lambda_{B(i)\,\max} = \lambda_{B(i)} + N_\varepsilon . \lambda_{B(i)} \cdot \Delta\varepsilon^+_{(i)}, \tag{12}$$

$$\Delta_{ch(i)} = \lambda_{B(i)\,\max} - \lambda_{B(i)\,\min}, \tag{13}$$

where i is the index of the FBG and takes values $i \geq 2$.

The number of FBGs on one optical fiber is given by the number of measurement channels that lie within the LED spectrum.

2.5. TDM and General Conditions

Quasi-distributed measurement with FBGs based on TDM uses Bragg gratings with equal Bragg wavelengths and very low reflectivity. A short duration impulse from the LED is launched via the circulator to the sensor array. At each FBG boundary, the pulse

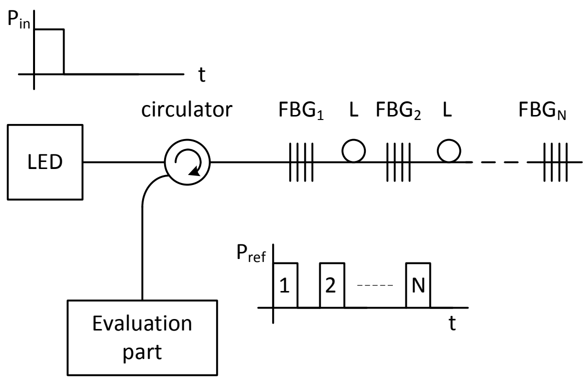


Fig. 5: The basic scheme of TDM using FBG sensors.

is partly reflected back to the processing unit (Fig. 5). The spectral characteristics of these reflected pulses include the information about the measured value [3], [4].

TDM requires the fulfillment of the two following conditions. Firstly the reflectivity of individual FBGs must be small enough for transmission of the optical pulse to the end of the sensor array and back to the processing unit. Secondly the width of input pulse T_i must be shorter than the time ΔT such that:

$$T_i < \Delta T = 2L\frac{n}{c}, \qquad (14)$$

where ΔT is the time taken for the light to traverse twice the distance between adjacent FBGs, L is distance between two adjacent FBGs, n is refractive index of the fiber core and c is the velocity of light in a vacuum.

The minimum period between input pulses is given by:

$$T = N \cdot \Delta T, \qquad (15)$$

where N is the number of Bragg gratings in the array.

Low reflectivity is essential in large sensor arrays to ensure sufficient back reflected power. Time division multiplex was experimentally used with FBG reflectivity ranging from -37 dB to -50 dB and successful measurement with 1000 FBGs was achieved [5].

2.6. The Effect of the Chromatic Dispersion

Sources like LEDs contain many wavelengths increasing the risk of chromatic dispersion. Furthermore, FBG arrays require relatively long optical fibers. At long fiber lengths, the effect of chromatic dispersion is more evident. The chromatic dispersion causes spreading of the optical pulses and an overlap of the reflected pulses occurs. The chromatic dispersion of the reflected pulse from the i^{th} FBG at the receiver is given by the relation:

$$D_i = 2 \cdot L \cdot i \cdot D_{ch}(\lambda) \cdot \mathrm{FWHM}_{\mathrm{LED}}, \qquad (16)$$

where i is the index of the FBG, $D_{ch}(\lambda)$ is the coefficient of chromatic dispersion and $\mathrm{FWHM}_{\mathrm{LED}}$ is the LED spectral width.

Consider an input pulse of duration 50 ns, ΔT = 100 ns and a source with a central wavelength of 1550 nm and linewidth of 40 nm. In this case, the chromatic dispersion for 3 470 FBGs is larger than the period of the output pulses resulting in an overlap of adjacent pulses.

2.7. The Effect of Reflectance

The reflectance is considerably influenced by the intensity of the reflected pulses [5]. The reflected power Pi from the i^{th} FBG is given by relation:

$$P_i(\lambda) = P_{in}(\lambda) \cdot R(\lambda)^i \cdot (1 - R(\lambda))^{2(i-1)}, \qquad (17)$$

where $P_{in}(\lambda)$ is the power of the input pulse, $R(\lambda)$ is the reflectivity of FBG, $1 - R(\lambda)$ is the transmission of FBG and i is the index of the FBG. The reflected power as a function of the number of FBGs in the array at various values of reflectivity is illustrated in the Fig. 6.

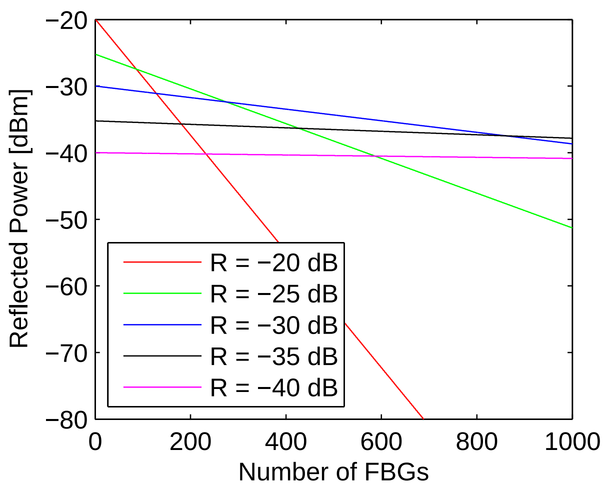


Fig. 6: The reflected power as a function of the number of FBGs in the array at various values of reflectivity R.

2.8. The Effect of Crosstalk

The guided light is partly reflected from each FBG both in the forward and backward directions. This results in multiple reflections between Bragg gratings.

Contributions from pulses reflected from various FBGs can arrive simultaneously at the processing unit. Fig. 7 illustrates the principle of first order crosstalk. The crosstalk pulse I_{212} and I_3 arrive at the processing unit simultaneously [3].

If the FBGs are identical and have a very low reflectivity then the first order crosstalk can be expressed by

$$C_i(\lambda) = \frac{(i-1)(i-2)}{2} \cdot R^3(\lambda) \cdot (1 - R(\lambda))^{2i-4} \cdot I_0(\lambda), \qquad i \geq 3. \tag{18}$$

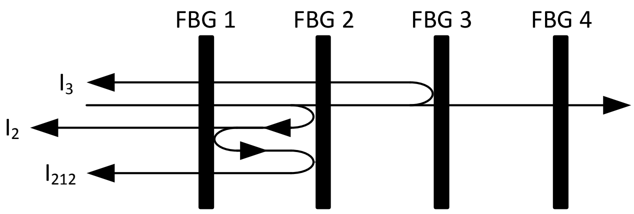


Fig. 7: The principle of first order crosstalk.

the simplified relation in Eq. (18), where $C_i(\lambda)$ is the error power that arrives at the processing unit simultaneously with the reflected power from the i^{th} FBG [6]. In Fig. 8 the values of the first order crosstalk for various values of FBG reflectivity is shown. The reflected power from i^{th} FBG must be considerably higher than the first order crosstalk. This is a crucial condition in TDM sensor array design.

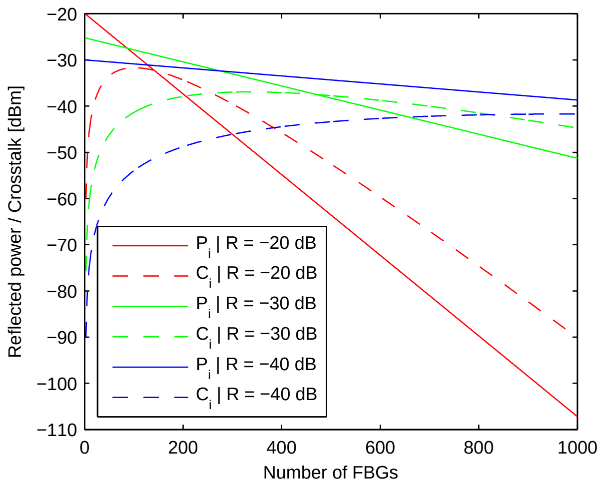


Fig. 9: A comparison of reflected power (P_i) and first order crosstalk (C_i) at various values of reflectivity.

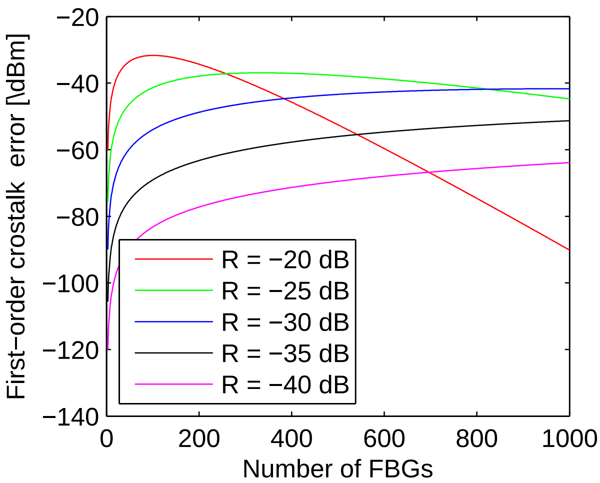


Fig. 8: The first order crosstalk at various values of reflectivity.

Figure 9 illustrates a comparison of the reflected power and the first order crosstalk. At an FBG reflectivity of −20 dB, the first order crosstalk is higher than the reflected power from FBGs with index $i \geq 141$. On the other hand, at an FBG reflectivity of −40 dB the reflected power from the 1000^{th} FBG is about −40.8 dBm while first order crosstalk is about 23 dB lower.

2.9. The Effect of Detector Limitations

In addition to the limitations discussed above, the reflected power from the FBG is also affected by Rayleigh scattering and by attenuation in the optical fibers [5]. However, these effects are very small and may be neglected. The detection limits of photodetectors are important too. The amount of reflected power from the last FBG must be higher than the detection limit of the photodetector, and also the reflected power from the first FBG must be within the dynamic range of the photodetector.

3. Simulation

Quasi-distributed sensors using WDM and TDM were designed and simulated in the OptiSystem software based on the mathematical relationships described above.

3.1. WDM Sensor Simulation

A broad spectrum LED at a wavelength of 1550 nm and linewidth 42 nm was used. The same measurement range of deformation from −500 to 1000 µstrain was used for all FBGs. The spectral width of the FBGs was set to 0.2 nm and the guard band between adjacent channels were determined by using equation 1.5 at 0.288 nm. By using equations Eq. (6) to Eq. (13), the Bragg wavelengths of individual measurement channels were determined. In Fig. 10 the spectra of 20 FBGs that all lie within the LED linewidth are shown. The spectra of two adjacent FBGs in the limiting case described above are shown in Fig. 11. As can be seen, the spectra of the two FBGs are easily distinguishable.

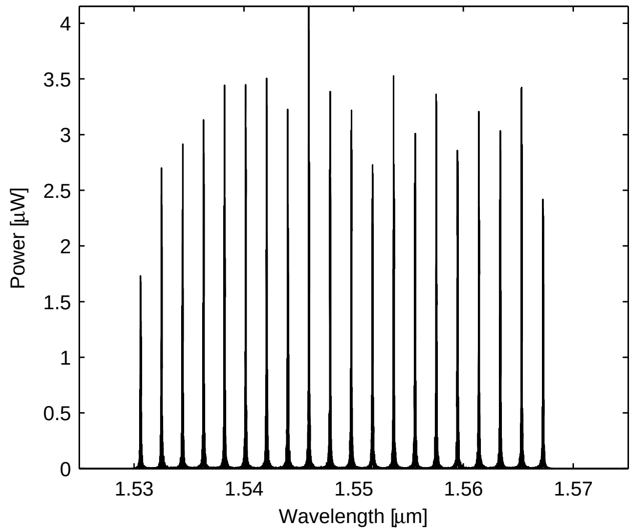


Fig. 10: Spectra of 20 FBGs.

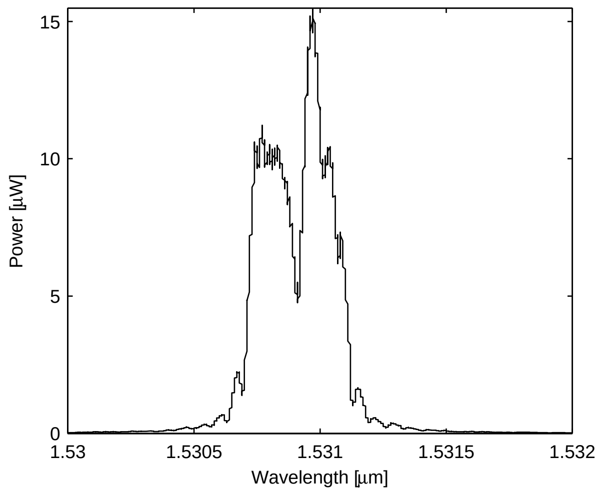


Fig. 11: Spectra of two adjacent strain measurement channels in the limiting case.

3.2. TDM Sensor Simulation

In the TDM simulation, the same broad spectrum LED was used as with WDM. The LED was modulated such that the output pulses were of 10 ns duration. This duration must be shorter than the time taken for the light to travel from one FBG to the second and back again. At a pulse duration of 10 ns, the value of ΔT was chosen to be 20 ns. Using Eq. (14), the distance between adjacent FBGs was determined to be around 2 m. For a sensor array of 20 FBGs on one optical fiber, using Eq. (15), the period of the input pulses must be at least 400 ns. FBGs with a reflectivity of 40 dB were selected. Pulses coming from the FBG sensor array are shown in Fig. 12.

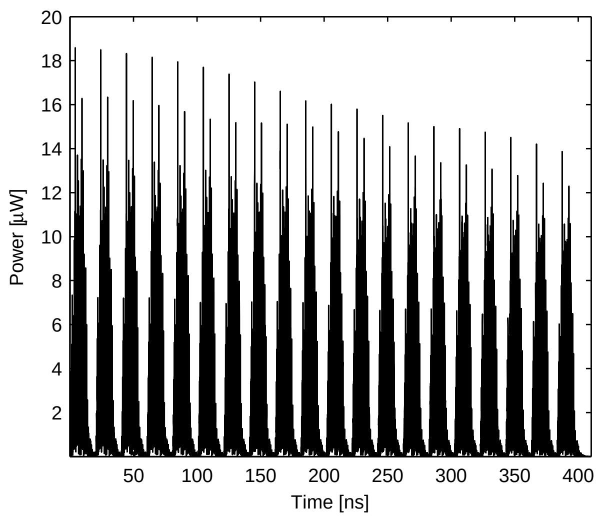


Fig. 12: Power response from a 20 FBG sensor array.

4. Conclusion

In this paper, WDM and TDM multiplexing techniques for quasi-distributed measurement using Bragg gratings was described. In addition, the mathematical relationships required to optimize the number of sensors were stated. For WDM, the relationships required to calculate the necessary Bragg wavelengths for a given strain or temperature measurement range were developed. Limitations in the use of TDM were discussed, including constraints on the pulse width, the effect of chromatic dispersion, the FBG reflectance, and the first order crosstalk. In consideration of these limitations, simulations using the OptiSystem software for both multiplexing techniques were undertaken.

WDM is limited by the measurement range, the spacing between adjacent channels, and the linewidth of the source and FBGs. An increase in WDM capacity is possible by using a source with a greater linewidth, by using FBGs with a narrower linewidth or improved spectral characteristics. For TDM, it is possible to increase sensor capacity by increasing the input pulse period or by decreasing the duration of the input pulse. Increasing the input pulse period reduces the measurement rate. Chromatic dispersion limits the minimum pulse width that may be used. The dominant effect is power limitation. The received power level decreases with increasing FBG index, i. To measure small power levels, the equipment with a sufficiently large dynamic range is required.

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References

[1] KERSEY, A. D., M. A. DAVIS, H. J. PATRIC, M. LEBLANC, K. P. KOO, C. G. ASKINS, M. A. PUTNAM and E. J. FRIEBELE. Fiber grating sensors. *Journal of Lightwave Technology*. 1997, vol. 15, iss. 8, pp. 1442–1463. ISSN 0733-8724. DOI: 10.1109/50.618377.

[2] TALAVERANO, L., S. ABAD, S. JARABO and M. LOPEZ-AMO. Multiwavelength fiber laser sources with Bragg-grating sensor multiplexing capability. *Journal of Lightwave Technology*. 2001, vol. 19, iss. 4, pp. 553–558. ISSN 0733-8724. DOI: 10.1109/50.920854.

[3] HU, C., H. WEN and W. BAI. A novel interrogation system for large scale sensing network with identical ultra-weak fiber bragg gratings. *Journal of Lightwave Technology*. 2014, vol. 32, iss. 7, pp. 1406–1411. ISSN 0733-8724. DOI: 10.1109/JLT.2014.2305714.

[4] DAI, Y., Y. LIU, J. LENG, G. DENG and A. ASUNDI. A novel time-division multiplexing fiber Bragg grating sensor interrogator for structural health monitoring. *Optics and Lasers in Engineering*. 2009, vol. 47, iss. 10, pp. 1028–1033. ISSN 0143-8166. DOI: 10.1016/j.optlaseng.2009.05.012.

[5] WANG, Y., J. GONG, B. DONG, D. Y. WANG, T. J. SHILLIG and A. WANG. A Large Serial Time-Division Multiplexed Fiber Bragg Grating Sensor Network. *Journal of Lightwave Technology*. 2012, vol. 30, iss. 17, pp. 2751–2756. ISSN 0733-8724. DOI: 10.1109/JLT.2012.2205897.

[6] ZHANG, M., Q. SUN, Z. WANG, X. LI, H. LIU and D. LIU. Green recovery: A large capacity sensing network with identical weak fiber Bragg gratings multiplexing. *Optics Communications*. 2012, vol. 285, iss. 13–14, pp. 3082–3087. ISSN 0030-4018. DOI: 10.1016/j.optcom.2012.02.100.

[7] WANG, Y., J. GONG, D. Y. WANG, B. DONG, W. BI and A. WANG. A quasi-distributed sensing network with time-division-multiplexed fiber bragg gratings. *IEEE Photonics Technology Letters*. 2011, vol. 23, iss. 2, pp. 70–72. ISSN 1041-1135. DOI: 10.1109/LPT.2010.2089676.

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