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Distinct enlargement of network size or measurement speed for serial FBG sensor networks utilizing SIK-DS-CDMA

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Abstract. Using the spectral selectivity and adjustable reflectivity FBGs are predestined for serial networking. Presently the addressing is realised by time division multiplex (TDM) or wavelength division multiplex (WDM). But these technologies have big disadvantages regarding the effective use of the prevailing resources time and wavelength, respectively. In this paper a new scheme capable of addressing a large number of FBGs in a single serial network is proposed and compared to TDM and WDM. Using all optical sequence inversion keyed (SIK) direct sequence (DS) code division multiplex (CDM) it overcomes the restrictions handling the resources time and wavelength without losing accuracy.

1. Introduction

Fibre Bragg Gratings (FBG) are small and lightweight, easy to handle and the measurable parameters are various, e.g. temperature, strain or concentrations [1]. The two properties spectral selectivity and reflectivity led directly to serial networks using wavelength division multiple (WDM) and time division multiple (TDM), respectively [2], with big disadvantages regarding the efficiency of resource utilization. In TDMA an optical impulse has to travel up to the last sensor and back again, before a new pulse can enter the network. Especially in large networks the information per time gets very low. Even more serious are the problems using WDMA. The network size is restricted to the relative small usable optical bandwidth of the source. In addition the FBG wavelength position and linewidth has to be allocated very accurately, which in turn leads to much higher costs and to low robustness.

Using our proposed system, sequence inversion keyed direct sequence code division multiple access (SIK-DS-CDMA), the FBG spectra can overlap and do not need to be highly accurate. A pulse train representing a unique code is sent into the network and will be reflected with a time shift at every sensor. Two pulses can directly follow after each other, what solves the information deficit of TDMA. Modulating the signal at the receiver side by the correct time adjusted code and integrating it over time, one gets back the sensor information plus some smaller distortions from other sensors (DS-CDMA). With the unipolar-bipolar conversion (SIK), bipolar processing can be achieved, which in the ideal case results in a completely undisturbed signal.

In chapter two a short overview over FBG will be given. Chapter three explains the DS-CDMA in general and the meaning of sequence inversion keyed (SIK) receiver scheme. The combination of both, the sensor and the multiplexing in a serial network will be described in detail in chapter four. The results of our simulation with 20 sensors that cover only a 2nm wavelength range can be found in chapter five. Chapter six concludes the paper.

2. Fiber Bragg gratings

Permanent FBGs were first demonstrated in 1978 by Hill et al. [3]. A periodic change of the core refractive index along the fibre causes a reflection of the light in a spectral range of $>0.2\text{nm}$. The main advantages are high variability, all-fibre geometry and potentially low cost. In [4] Turan Erdogan gives a very good basic description of spectral calculations. Assuming the index change is uniform across the fiber core (x,y) and nonexistent outside, the coupling coefficient along z can be described as

$$K_{kj}^t(z) = \sigma_{kj}(z) + 2\kappa_{kj}(z) \cos\left[\frac{2\pi}{\Lambda}z + \phi(z)\right] \quad (1)$$

In this equation $\sigma_{kj}(z)$ and $\kappa_{kj}(z)$ are the period-averaged and periodic coupling coefficients, respectively, $\phi(z)$ is the grating chirp and Λ the nominal period of the index change. Each of these parameters can be varied during the production process and in this way the properties of the FBGs are adapted to its application. For our simulation we chose an uniform FBG profile due to very complex calculations of the nonuniform type, even though every other type could also be implemented.

Besides communication purposes foremost as optical filter, FBGs are also very practicable for sensor applications. Variation of the grating properties, caused e.g. by a change of temperature or strain, influences the maximum wavelength λ_{\max} of the reflected light and can be measured. The typical strain (ε) response at constant temperature is found to be

$$\frac{1}{\lambda_{\max}} \frac{\delta\lambda_{\max}}{\delta\varepsilon} = 0.78 \cdot 10^{-6} \mu\varepsilon^{-1} \quad (2)$$

so $\delta\lambda_{\max}$ is $0.64\text{nm}/1000\mu\varepsilon$ for an 820nm FBG. The normalised thermal response at constant strain is

$$\frac{1}{\lambda_{\max}} \frac{\delta\lambda_{\max}}{\delta T} = 6.67 \cdot 10^{-6} \text{ } ^\circ\text{C}^{-1} \quad (3)$$

A 100°C temperature change at the same FBG causes a $\delta\lambda_{\max}$ of 0.55nm . Both reactions are reversible and linear in a wide range.

To realise a serial sensor network, in which the spectra of at least two FBG can completely overlap, the maximum reflectivity of each sensor has to be smaller than 100%. How many sensor spectra can overlap depends on system properties like optical power of the source, losses or sensitivity of the receiver.

3. SIK-DS-CDMA

Once developed by military for secured transmission, CDMA can now be found e.g. in satellite or mobile phone communication networks. But also in the optical part CDMA becomes popular to enhance the capacity of TDMA and WDMA networks [5]. The reasons are particularly the simplicity of implementation, utilisation of resources as well as the distortion insensitivity in relation to interfering users and multi-path propagation. Another term for CDMA is spread spectrum technique, because of the widened original data spectrum in the frequency domain. This spreading can be realised with different methods and usually contains the address information.

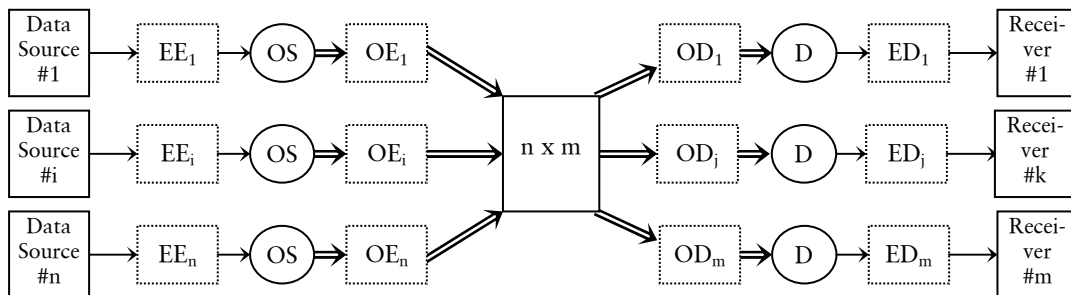


Figure 1. A universal schematic diagram of optical CDMA: EE: electrical encoder; OE: optical encoder; OD: optical decoder; ED: electrical decoder; OS: optical source; D: Detector; \rightarrow : electrical connection; \Rightarrow : optical connection

The general principle for optical CDMA is illustrated in Fig. 1. Address coding takes place either in the electrical (EE) or in the optical domain (OE). All channels use the same optical band at the same time (synchronous or asynchronous). At the receiver side the decoding happens by means of correlation with the desired code, again, either in the optical (OD) or electrical (ED) path. In the autocorrelation case the data signal is rebuilt ideally, whereas in the cross-correlation case the unwanted data signals remain in the spread condition. Nearly all properties of light propagation can be used for coding. Besides the later described incoherent DS-CDMA also the coherent type, furthermore e.g. phase shift keying, coding of subpicosecond impulse spectra, even wavefronts is practicable. [6]

In direct sequence CDMA the information is coded by means of OOK. The data are modulated by a chipstream (for a better distinction the states of the code are called chips rather than bits) with a chip to bit ratio much bigger than one. If on the receiver side the signal is again modulated by the correct and not time shifted code and afterwards integrated over a bit length, one gets the value of one bit multiplied by the code weight. The code weight P is the number of "1" in a code, if "1" is assumed as "light on". In comparison, a fault or time shifted code causes $1 \cdot 0 = 0$, so the value after integration will be smaller than the correct one. Sending different coded information at the same time and wavelength in one fiber, receiver side multiplication (correlation) yields the wished signal plus multiuser interferences (MUI). The signal to MUI ratio will decrease with an increasing number of interfering channels but also depends in high degree on the used code. Orthogonal codes, codes that match in not more than one chip, offer the best result but have the disadvantage of a small code weight. If all channels send at the same time, as it has to be assumed for a serial FBG network, the maximum number of addressable users is equal to P , because the value after integration is P for autocorrelation and $P-1$ for MUI as the sum of all crosscorrelations with orthogonal code.

Because of possible cancellation bipolar processing offers a much better signal to MUI ratio. But, except for using two paths, this is not possible in incoherent optical systems as described above. By splitting the optical path at the receiver side into two and applying an optical multiplication with the desired code and its complement together with a subsequent detection using balanced diodes, the unipolar chip sequence can be correlated with a bipolar code. This unipolar-bipolar correlation process named sequence inversion keying (SIK) maintains the properties of a bipolar-bipolar one but is much easier to implement [7]. One condition is the use of balanced codes, which have an equal number of "1" and "0". As another description of SIK one can say, that in the path of complement code only signals of unwished channels will pass. If the number of these chips is same as the distortions in the direct coded path (MUI, balanced code), the subtraction will cancel out all MUI. The effect increases with growing code length and would be ideal for a constant crosscorrelation function of half code weight.

4. SIK-DS-CDMA addressed FBG-Sensor-Network

Our new addressing scheme for serial FBG networks is shown in Fig. 2. Continuous light of a SLD is modulated by a balanced PN-code using a LiNb modulator. The pulse train reaches the FBG network and will be reflected at each FBG with a time shift. Two conditions can be determined: the time shift between two FBGs has to be larger than one chip length and second, the reflectivity of one FBG has to be smaller than 100%, as mentioned in chapter two. The addition of all reflections is divided in two paths. In the left, the direct path, the signal is modulated by the correct time shifted code to address one certain FBG. Here one gets the wished information together with parts of other FBGs. The right path modulates the signal with the inverted code, delayed by the same time shift, to obtain the benefits of SIK. The two spectrometers integrate the time signals and return the wavelength information of the respective path. For the following subtraction and calculation of the wavelength shift and in that way the equivalent change of the sensed term, a computer can be used.

There are some important differences compared to Fig. 1. First, all not coded data are always "1" (SLD as data source). Second, all channels are modulated by the same code. Due to the time shift of one chip length between two reflections, the response is a crosscorrelation for all unwished signals. Here the distortion insensitivity of CDMA in relation to multi-path propagation will be utilised.

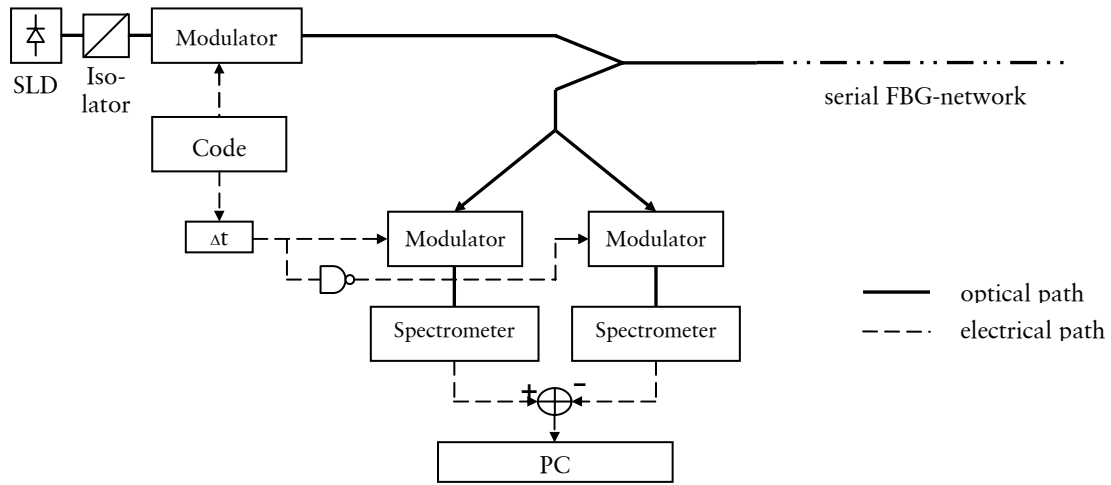


Figure 2. Addressing of a serial FBG network by SIK-DS-CDMA

Another special point is the SIK. In communication systems using SIK-DS-CDMA the spectral information is unimportant. Because both, information and coding is placed in time domain, it does not matter, if the disturbing channels influence the spectrum of the wished one with different intense. Cancellation can happen between all channels. For our proposed system this fact is different, here the information lays in the spectrum, whereas coding occurs in time domain. To return only the spectrum of the chosen FBG, all unwished channels have to cancel out itself during the integration process. In addition to the autocorrelation peak the probability of cancellation increases, if long balanced codes are used. Both will effect the signal to MUI ratio positively.

But what are the advantages over WDMA or TDMA? Assumed the line width of an FBG is 0.2nm (FWHM) at 820nm and the temperature has to be measured in a 100°C range, the spectral separation between two FBGs has to be at least 0.95nm. Using a SLD with a bandwidth of 20nm, the network capacity is 21 FBGs. To enhance this number or the measurable range, a second SLD could be included, which results in higher costs. In comparison our simulation shows a capability of 20 FBGs in a 2nm range only by overlapping their spectra and thus our technique overcomes this major restriction.

TDMA also solved this problem [8], but here the amount of information per time becomes small in larger networks. Before a new impulse can launch the first FBG of the network, the reflection of the last has to pass this point. Thus, common sampling techniques suffer restrictions. Because of the path splitting at the receiver side our system needs in the ideal case two impulses for the same intensity of the TDM case. So for a balanced code the code length has to be four. Assuming a running time between neighboured FBGs of half the impulse length every network of our scheme that exceeds four FBGs offers more information per time than using TDMA. If the 50%-coupler and the two modulators were replaced by a Mach-Zehnder modulator with complementary outputs, even networks of more than two sensors exceed the time multiplexed version. The problems of overlapping spectra and parasitic double reflections are same in CDM and TDM [2], whereby the latter effect can be heavily reduced by a good dimension of reflectivity.

5. Simulation

To prove our expectations a complex simulation was programmed based on following network data:

Table 1: Network properties

Code	Balanced PN		Max. of first FBG @	799.48nm
Codelength	40chips		Spectral separation betw.	53pm
Chipfrequency	200 Mchips/s		2 FBG	
Number of FBGs	20		FWHM FBG spectrum	200pm
Distance between 2 FBG	1m		Max. reflectivity	10%

In Figure 3a the scaled data of the direct and inverted path spectrometer can be seen including the original FBG spectrum of FBG10. The direct path is equal to DS-CDMA without SIK. For the used balanced pseudo-noise-code the MUI is very strong. The spectral maximum is shifted and the first minima close to the maximum not recognisable. To obtain the wished frequency shift only maximum detection would be possible but not very accurate. As expected, the spectrum of the inverted path shows its maxima at the positions of biggest error, near the first minima of FBG spectrum and a local minimum at FBG maximum. After subtraction the MUI is heavily reduced as can be seen in Figure 3c. There is still a small shift in the maximum, which is caused by the overlapping of the FBG spectra. The minima are clearly visible and could be included in calculations of the sensed value.

The signals of the first and last sensor are shown in Figure 3b and Figure 3d, respectively. Again the first minima are at the right wavelength position. So not only peak detection but also correlation and other techniques can be used for the calculation of the sensed term.

With 40 chips and 20 sensors the code is still very short. Due to the balanced code the information per time is 20 chips, corresponding to 100ns continuous measurement time. Assuming a minimum integration time of 1ms in the CCD-spectrometer, the code length could be 200,000 chips with 0.5ms measurement time and a much higher signal to MUI ratio. A TDMA network of same dimension needs a delay between two impulses of ca. 190ns. With the 5ns impulse length and 1ms integration time this results in roundabout 26.5 μ s measurement time, but with double intensity. Hence our system works better by nearly the factor 10.

With the 20nm optical source of a WDMA system mentioned above, our system could contain ca. 370 FBGs. Assuming furthermore a 0.95nm separation, this leads to an improvement of more than the factor 17.

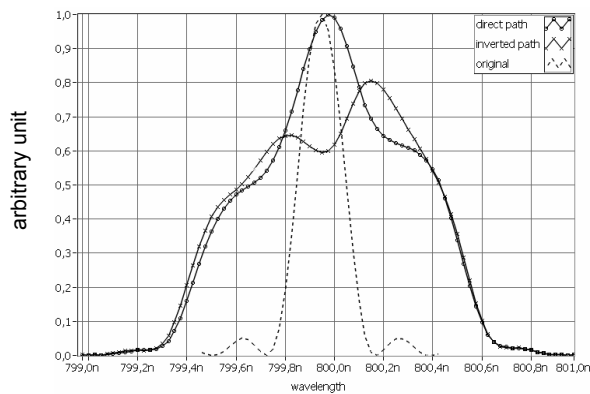


Figure 3a. FBG spectrum and scaled output of direct and inverted path for FBG 10

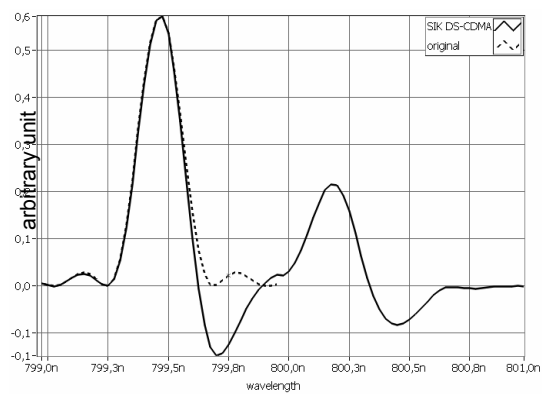


Figure 3b. Spectr. after subtraction for FBG1

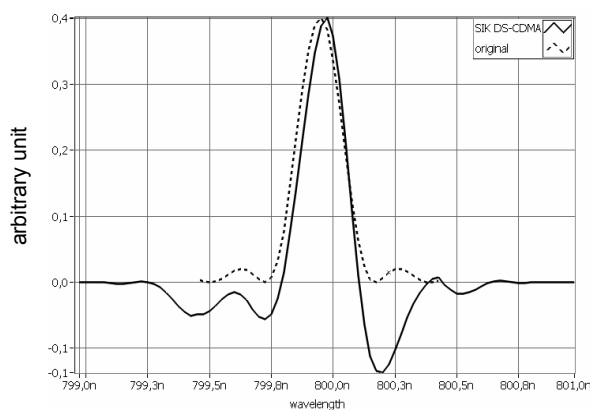


Figure 3c. Spectr. after subtraction for FBG10

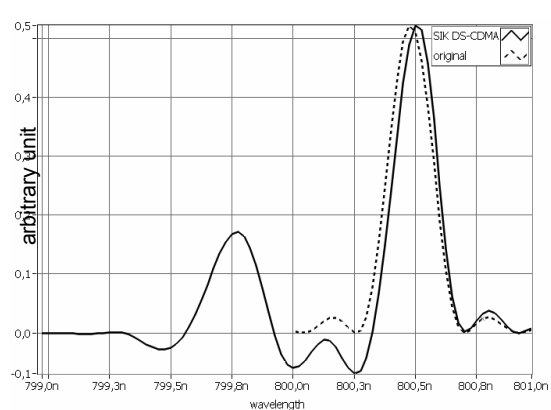


Figure 3d. Spectr. after subtraction for FBG20

Still we ignored noise and non-linearities for all network types. Also the code is not yet optimised, just balanced and random. Here some work has to be done as well as in terms of recognition of the FBG spectra. But presently the practical prove of these very positive simulation results is our main topic.

6. Conculsion

We presented a new effective scheme for addressing FBG sensors in serial networks. The used SIK-DS-CDMA offers important advantages compared to presently used WDMA and TDMA systems. In a simulation we showed, that our system is superior to TDMA by the factor 10 regarding the information per time and factor 17 in network size for WDMA.

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