Fiber Bragg Grating Compression-based Tuning Device for Reconfigurable OADM

Roberson A. Oliveira, Carlos E. N. Mayer and Alexandre A. P. Pohl
CPGEI, Federal University of Technology-Paraná
Curitiba, Paraná, Brazil.
Corresponding author: pohl@utfpr.edu.br

Jucélio T. Pereira
Department of Mechanical Engineering
Federal University of Paraná
Curitiba, Paraná, Brazil.

Abstract—**In this work a fast Bragg grating-based tuning device, working according to the mechanical compression of the fiber, is demonstrated. The device achieves a tuning range of 10 nm and presents tuning speeds up to 15 nm/ms. The component can function as the basic element in wavelength routers and add-drop multiplexers.**

Keywords: *Fiber Bragg Gratings, tuning device, OADM.*

I. INTRODUCTION

The development of wavelength division multiplexing (WDM) systems has provided a huge increase in the transmission capacity of optical links. Moreover, the maturity of optical network devices such as add-drops and optical cross-connects motivates the migration of statically designed point-to-point optical links to dynamically reconfigurable optical networks. However, reconfiguration requires the employment of components that allow a wide and rapid change of optical channels, requiring devices that respond, at least, in the milliseconds or microsecond time frame. Channel tuning can be achieved through several techniques and fiber Bragg gratings (FBG) offer a practical alternative for achieving wide tuning, once this can be accomplished by the application of external stimulus like temperature [1] and strain [2, 3]. However, temperature-based systems have some disadvantages like low speed. Additionally, longer Bragg wavelength shifts are only possible by applying high temperatures, whereby temperatures above 500 ^{o}C generally damage the fiber and the grating. On the other hand, devices based on the application of longitudinal strain requires external applied forces easily achieved using piezoelectric actuators (PZTs) [4], magnetic actuator [5] or step motors [6]. Literature reports longitudinal strain systems based on the traction and/or compression working principle, with different performance for tuning speed and tuning range. For instance, a tuning range of 16 nm with a tuning speed of 0.5 nm/ms is reported in [7] using a magnetic actuator for traction. A tuning range of 32 nm with an estimated tuning speed of $3.2\text{x}10^{-2}$ nm/ms is reported in [6] using step motor for compression. Another system is described in [8] with a tuning range of 45 nm and tuning speed of 19 nm/ms using high-voltage (0 to -1000 VDC) driven actuators for traction and compression.

In this work, we present the design, fabrication and test of a FBG tuning device based on the compression technique, which provides a tuning range of 10 nm and tuning speeds up to 15 nm/ms, but using low-voltage (0 to +100 VDC) piezo actuators.

II. AXIAL COMPRESSION IN THE FIBER

For achieving wide tuning in fiber gratings based on traction and/or compression one needs to understand how longitudinal strain is applied onto the fiber. The first assumption is to consider the fiber as a thin cylindrical, linear, homogenous, isotropic and elastic bar. According to the linear theory of elasticity, this hypothesis is valid for stress estimation with an error of less than 5.6% for applied strain < 2% [9]. Considering this constraint, when a load is applied longitudinally (for instance, in the x direction, which corresponds to the fiber axis), the one-dimensional infinitesimal strain is given by

$$\varepsilon_x = \frac{\partial u}{\partial x}, \tag{1}$$

where u is the displacement function. Under the assumptions of a linear behavior, the relationship between the stress and the strain is given by

$$\sigma_x = E\varepsilon_x, \tag{2}$$

where σ_x is the longitudinal stress, ε_x is the longitudinal strain and E is the Young modulus for the silica fiber. On the other hand, the Bragg wavelength shift experienced by the grating is proportional to the applied longitudinal strain as computed by [3]

$$\Delta\lambda_B = \lambda_B\varepsilon_x\left\{1 - \frac{n^2{}_{eff}}{2}\left[p_{12} - \nu\left(p_{12} + p_{11}\right)\right]\right\}, \tag{3}$$

where $\Delta\lambda_B$ is the Bragg wavelength shift, λ_B is the Bragg reference wavelength for a grating free of applied strain, n_{eff} is the effective index, p_{11} and p_{12} are components of the strain optic tensor and ν is the Poisson's ratio, which represents the ratio between the transversal and longitudinal strains. Equation (3) is used to estimate the tuning range, when gratings are submitted to traction and/or compression, given that the device does not undergo temperature changes.

On the other hand, equation (3) considers primarily the grating under the influence of static forces. However, if the strain is time dependent, the same expression provides the clue for asserting the time behavior of gratings. In this case, it can be rewritten as a relationship between $\Delta\lambda_B$ and ε_x in the time domain if the remaining parameters are taken as constants:

$$\Delta\lambda_B(t) = \lambda_B \varepsilon_x(t)\left\{1 - \frac{n^2{}_{eff}}{2}\left[p_{12} - \nu(p_{12} + p_{11})\right]\right\}. \quad (4)$$

Thus, the temporal behavior of ε_x dictates the temporal behavior of $\Delta\lambda_B$ in a linear way. This approach is necessary in order to estimate the tuning speed as the ratio of $\Delta\lambda_B$ and the time gap in which the wavelength shift is achieved, as will be described further on.

III. COMPRESSOR DESIGN

The design of a device based on compression requires several considerations of size, ways of applying forces on the fiber and, particularly, the way in which the fiber is fixed and withstand the compression strain. One particular mechanical structure that can be used for providing compression is seen in Fig. 1. The component consists of a metal frame shaped in the form of a quadrilateral, with two narrow metal beams stretching from the sides across the central part of the frame. The fiber is placed and fixed by means of glue in a groove fabricated in the middle of the beams. The Bragg grating is positioned in the middle of the two beams. Compression is achieved with the help of a piezoelectric actuator placed across the vertical axis of the metal frame, between its bottom and upper sides. As the actuator is stretched by means of an applied voltage, the metal frame is pulled in the vertical direction, making the beams come close to each other in the central part. By doing this, the fiber and grating are submitted to a compression load, which leads to a change in the grating parameters, as given by (3). In order to avoid buckling of the fiber between the beams, which may lead to its disruption, the fiber is protected with a sleeve. The design of the metal frame was performed using a CAD software and ANSYS™ [10] for estimating the load to which the frame stands without being deformed.

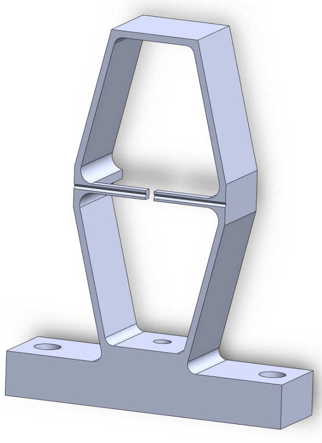

Fig. 1. Metal frame used in the compression-based device.

For the structure shown in Fig. 1, loads up to 1000 N (45 μm maximum displacement) are allowed without deformation.

IV. TUNING RANGE AND SPEED

The tuning range of the Bragg wavelength is achieved as a result of the strain experienced by the grating when it is compressed, by the application of voltage to the piezo actuator over its allowed range (in this case, from 0 to +100 VDC). This range can be measured with an optical spectrum analyser, whose results are shown in Fig. 2. One observes that for the current device the maximum tuning range is limited to 10 nm. Within this range the shift in wavelength is linear and reproducible over voltage. Besides the tuning range, the other important characteristic is the tuning speed. Tuning occurs in a time interval which, for many applications, should be as short as possible. This way, tuning speed turns out to be an important parameter for reconfigurable devices and should be properly measured. In the case of Bragg gratings, tuning speed, v, can be defined as the ratio between the maximum wavelength shift (tuning range) and the time needed to perform the shift. For estimating the speed one is primarily concerned with the measurement of two parameters: the range in which the wavelength is tuned and the time in which this occurs, as given by

$$v = \frac{\Delta\lambda}{\Delta t} \text{ nm/ms,} \quad (5)$$

where $\Delta\lambda$ is the tuning range and Δt is the time interval. Due to its slow response, optical spectrum analysers are not suitable for measuring the time interval. Therefore, these parameters need to be measured or estimated, which require a reference from which both are determined.

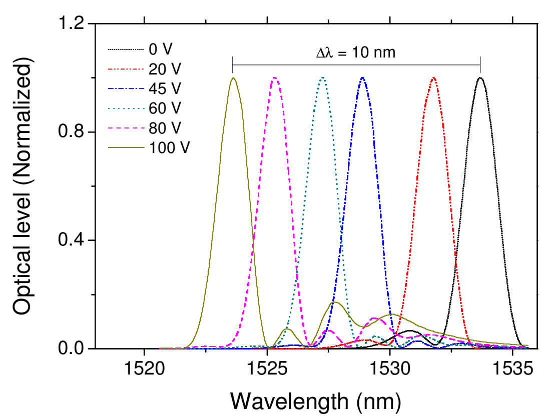

Fig. 2. Tuning range of the designed compressor.

The experimental setup used for obtaining the wavelength shift and the time interval is seen in Fig. 3. The idea behind the measurement is to apply a step impulse of known voltage to the piezoelectric transducer and observe the time response by means of a fast photo-detector (response time < 1 ns) and a digital oscilloscope when the grating is moved from its rest position. For controlling the voltage applied to the actuator a function generator was used. The generator output was connected to the actuator driver, which provides a ten times signal amplification. The function generator was also controlled externally through the parallel port of a personal computer by means of a routine written in LabView. The control is necessary for sending only one voltage square pulse to the actuator at a time. The slope of the electric square pulse served as the reference for the onset of the voltage to the piezoelectric transducer and for observing the delay in the photo-detector response. Both excitation and response waveforms were observed in a digital oscilloscope with the corresponding data sent to the personal computer for analysis over the GPIB interface.

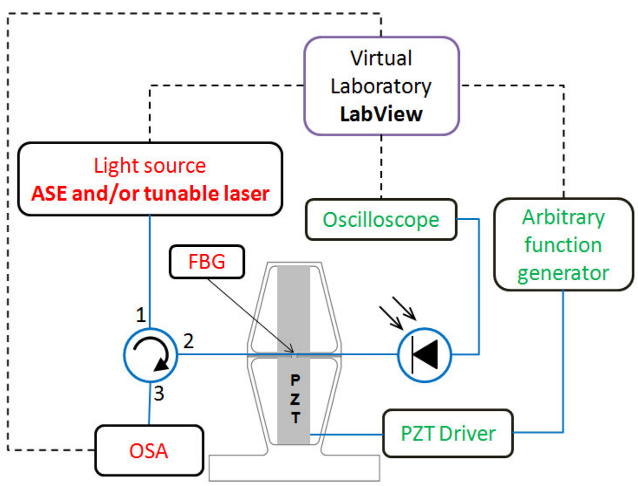

Fig. 3. Experimental setup for measuring the tuning speed.

Fig. 4 shows a typical response seen on the oscilloscope screen. The dashed lines show the behaviour of the voltage rise (Fig. 4*a*) and drop (Fig. 4*b*) of the square pulse, when it is applied to the actuator. The solid curves show the photodetector response. Considering the time interval as the time measured between the two vertical traces shown in the figures, one can then calculate the tuning speed. For the rise of the square pulse, the tuning speed was calculated as 2.59 nm/ms, while for the fall, the tuning speed was 15.15 nm/ms. The difference in the tuning speed is due to the blocking force experienced by the PZT when increasing the load. During the fall of the electric pulse, the fiber is released from strain, making it return faster to the rest position.

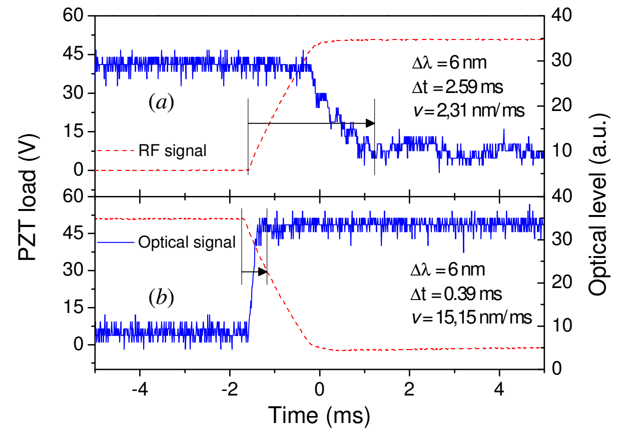

Fig. 4. (a) Rise of the PZT load and (b) drop of the load. For the case when the load increases, the PZT experiences a blocking force.

In a past work we have demonstrated the operation of a 4-channel reconfigurable add-drop multiplexer based on fixed Bragg gratings. Channel reconfiguration was achieved using 1x2 and 2x2 discrete optical switches that were driven by TTL voltage provided by an electronic circuit under the supervision of a microcontroller [11]. The use of many switches (a total of five in that prototype) causes high insertion losses that can be avoided with the employment of a different configuration using the present tuning device. Such configuration is seen in Fig. 5 for the same number of channels. In place of the optical switches, one can cascade four mechanical structures in a row, whose fibers containing the gratings are spliced to each other. Each FBG can be individually tuned over the external controller. The configuration is still under construction and tests results are not available at the present time. However, this configuration is expected to have less insertion loss and be of much lower cost.

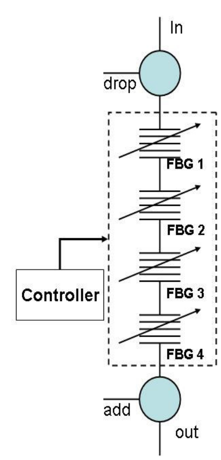

Fig 5. Configuration of the proposed reconfigurable OADM.

V. CONCLUSIONS

We have presented a Bragg grating-based tuning device, whose working principle relies on the compression of the fiber. The structure allows tuning in a 10nm range. Within this range the shift in wavelength is linear and reproducible over voltage, making it very reliable for applications in WDM networks, where channel reconfiguration is required. The range is limited by constraints that act to reduce the compression applied to the fiber. For instance, as the compression strength rises, the fiber suffers buckling between the beams in the central part of the mechanical frame. This contributes to release the strength and also leads to the breaking of the fiber. Tuning speed is the other important factor in reconfigurable devices. Although different speeds are achieved during the rise and fall of the electric pulse (2,6 nm/ms and 15,2 nm/ms, respectively), the present device can still sweep the whole range of the C-band in a very short time. Considering the reconfiguration time of optical channels in SDH networks (50 ms), the device demonstrated here can work well under the required limit.

ACKNOWLEDGMENT

This work received financial support from CNPq (473690/2007-01). Roberson A. Oliveira thanks the support of CAPES by means of PhD scholarship and Carlos Eduardo N. Mayer thanks the support of CNPq by means of a PIBIC scholarship. The authors also thank the fiber sensor research group at PUC-Rio for providing some of the gratings tested with the compressor.

REFERENCES

[1] J. A. Rogers, P. Kuo, A. Ahuja, B. J. Eggleton, R. J. Jackman, "Characteristics of heat flow in optical fiber devices that use integrated thin-film heaters," *Applied Optics*, vol. 39, no. 28, pp. 5109-5116, 2000.

[2] N. Mohammad, W. Szyszkowsky, W. J. Zhang, E. I. Haddad, J. Zou, W. J. Jamroz, and R. Kruzelecky, "Analysis and development of a tunable fiber Bragg grating filter based on axial tension/compression," *J. Lightwave. Techn.*, vol 22, no. 8, pp. 2001-2013, August 2004.

[3] P.T. Neves Junior, "Análise Temporal do Espectro Õptico em Redes de Bragg em Fibra", Tese de Doutorado, CPGEI, *Universidade Tecnológica Federal do Paraná*, 2008.

[4] W. Zu and X. Gu, "Fast Fiber-Optic Tunable Filter based on Axial Compression of a Fiber Grating", *Applied Optics*, vol. 45, no. 25, pp. 6457-6462, September 2006.

[5] S. Jin, H. Mavoori, R. P. Espindola, L. E. Adams, and T. A. Strasser,J. "Magnetically tunable fiber Bragg gratings," in *Proc. Optical Fiber Communications Conf. (OFC'99)*, San Diego, CA, Feb. 21–26, 1999, Paper ThJ2, pp. 135–137.

[6] G.A. Ball and W.W. Morey, "Compression-tuned Single-frequency Bragg Grating Fiber Laser", *Optics. Lett*, vol. 19, no. 23, pp. 1979-1981, December 1994.

[7] S. Jin, H. Mavoori, R.P. Spindola, L.E. Adams and T.A. Stresser, "Magnetically Tunable Fiber Bragg Gratings", *Proceedings of Optical Fiber Conference*, San Diego, USA, paper ThJ2, pp. 135-137, 1999.

[8] A. Iocco, H.G. Limberger, R.P. Salathé, L.A. Everall, K.E. Chisholm, J.A.R. Williams and I. Bennion, "Bragg Grating Fast Tunable Filter for Wavelength Division Multiplexing", *J. Lightwave. Techn.*, vol. 7, pp. 1217-1221, 1999.

[9] S. P. Timoshenko and J. N. Goodier, *Theory of elasticity*, McGraw-Hill, Auckland, 1970.

[10] ANSYS, http://www.ansys.com/, accessed on 01-05-2010.

[11] F. Küller, J.C.C. Silva, P.T. Neves Jr, P.V. Cosmo, J.L. Fabris, H. J. Kalinowski and A.A.P. Pohl, "Large Bandwidth Fiber Bragg Gratings for CWDM Systems", *Journal of Microwaves and Optoelectronics*, v. 8, p. 65-77, 2009.