

BGPP Conference 2001

4-6 July 2001

Istres, Italy

Effect of phase shift perturbations and complex local time delay in fiber Bragg gratings

Fabio Ghiringhelli, Carlos Alegria, and Michalis N. Zervas[†]

Optoelectronics Research Centre, University of Southampton,
Southampton, SO17 1BJ, U.K.

Tel.: +44 (0)23 8059 7673, Fax: +44 (0)23 8059 3149,

E-mail: fg1@orc.soton.ac.uk

[†] on sabbatical leave to Southampton Photonics Inc.

Abstract: The effect of introducing a phase shift inside a fiber Bragg grating is addressed and related to the time spent in the defect position by light. The impact on phase errors characterization in gratings is discussed.

© 2001 Optical Society of America

OCIS codes: (050.2770) Gratings; (050.5080) Phase shift; (060.2340) Fiber optics components.

The analysis of the effect of a localized perturbation inside a grating is interesting both from an application and a more fundamental point of view. So far, random phase errors distributions have been considered and their impact on fiber Bragg grating performance studied, taking into account variations both in the reflectivity spectrum and the time delay characteristics [1]. But the actual position of phase errors is important too, as Weber and Wang showed considering the effect on the phase of reflected light for the particular case of in-band propagation in multilayer dielectric mirrors [2]. A general approach to the problem has been developed by Furman and Tikhonravov [3] in connection to multilayers applications. Moving a defect along the grating length provides a longitudinal characterization that is expected to give useful information for grating design. The grating regions which are more likely to affect light propagation at specified wavelengths can be identified, with direct application in robustness analysis, energy storage and dispersion characterization. On the other hand, this approach can give deeper insight about the mechanisms related to multiple scattering and time delay build-up in gratings.

It has been shown [4] that, considering an infinitesimal phase shift $d\phi$ introduced at a certain position z , the corresponding variation in the reflection and transmission coefficients is given by:

$$r(z) = r_0 e^{-jd\phi N_R(z)} \quad t(z) = t_0 e^{-jd\phi N_T(z)} \quad (1)$$

where r_0 and t_0 are the unperturbed grating coefficients, $r(z)$ and $t(z)$ are the position dependent coefficients of the perturbed grating, and $N_R(z)$ and $N_T(z)$ can be interpreted as the effective number of passes experienced by the reflected and transmitted light in the perturbed region, respectively. From this point of view, a relationship between localized perturbation and time spent by light in each grating region is apparent, since $N(z) \doteq \frac{\tau(z)}{\tau_0}$ where $\tau(z)$ is the local time delay inside the grating at position z along an infinitesimal dz and τ_0 is the corresponding single-pass time. The proposed analysis can be applied to the characterization of the local time delay for both transmitted and reflected light independently. Actually, $N(z)$ is expected to be a complex number, since any perturbation affects both the phase and the amplitude of the grating response through the real and imaginary part of $N(z)$, respectively. Therefore, $Re\{N(z)\}$ shows the impact of the localized phase shift on the time delay (i.e. dispersion) of the grating. On the other hand, $Im\{N(z)\}$ gives the corresponding effect on the variation of grating reflectivity and transmissivity.

The apparently odd introduction of complex time delays has already been proposed in different contexts (i.e. interpreting tunneling phenomena in band-gap structures and evanescent propagation), and a detailed analysis of complex transversal time based on Feynman paths has been successfully applied to a simple Fabry-Perot cavity [5]. This approach has been extended to arbitrarily complex structures by splitting the grating into several sections and considering an equivalent Fabry-Perot cavity for each section [4]. The transmitted and reflected fields are expressed in term of components experiencing multiple reflections in the cavity and a weighted average over all the possible classical paths is performed. Therefore, analytical expressions of the number of passes $N(z)$ can be derived for both reflected and transmitted light.

In this paper we measure the imaginary part of the local time delay by introducing a phase shift in the grating and monitoring the corresponding transmissivity and reflectivity changes. The experimental setup

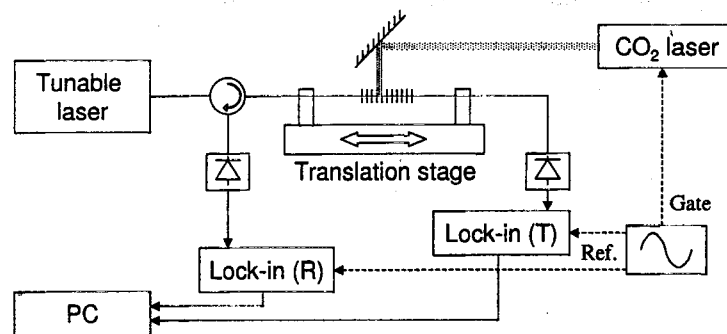


Fig. 1. Experimental setup used for the characterization of reflectivity and transmissivity variation due to phase shifts induced by CO_2 radiation absorption.

is a variation of the one used by Brinkmeyer *et al.* for grating strength and chirp characterization [6], and it is shown in Fig. 1. Light from a tunable laser diode is launched into the grating, which is mounted on a translation stage and perturbed by a non-destructive local heating induced by a CO_2 laser beam. The CO_2 power output is gated with a 2 Hz modulation signal and the corresponding disturbance signal is detected via a lock-in amplifier (time constant $\tau = 3$ s) for different wavelengths, both inside and outside the band-gap. Such a low modulation frequency has been selected to maximize the magnitude of the AC component of the perturbed signal. Both the transmitted and reflected signals are simultaneously detected, allowing a direct comparison irrespectively of source wavelength fluctuations or environmental changes. Due to the unavailability of a focusing lens, a 2 mm CO_2 spot size is scanned along the grating. The stage scanning speed is set to 1 mm/s, giving an effective spatial resolution of 3 mm, comparable with the dimensions of the perturbation, over the lock-in integration time constant. Therefore a relatively long, low index-change grating has to be used to allow a sufficient spatial resolution of the grating features. The tested grating is uniform, 40 mm long, and has estimated refractive index modulation $\delta n \simeq 3.4 \cdot 10^{-5}$. The minimum transmissivity is $T_{min} = -18$ dB and the -1 dB bandwidth is 0.043 nm.

The measured data (dotted line) are shown in Fig. 2 and compared with simulations. The grating has been characterized at two different wavelengths both inside and outside the band-gap to show how each wavelength is affected by the induced perturbation. The actual extent of the grating along each scan is marked. The measured signals have been normalized since the two detectors have different responsivities, the lock-in settings are independently set, and no direct comparison is possible. They show the expected complementary behaviour as required by energy conservation. The corresponding uniform grating simulations (dashed line) have a symmetric behaviour, as expected for symmetric structures. The asymmetry both in the in-band and in the out-of-band measurements suggest the presence of a non-ideal non-uniform grating profile. To test this hypothesis, we have inserted the measured reflectivity and time delay of the actual grating into a recently developed layer-peeling inverse scattering technique [7] to calculate the corresponding refractive index profile. The limited bandwidth of the measured spectrum and the windowing process necessary to obtain a causal and physically realizable time response limit the resolution of the reconstructing algorithm. This results in a corresponding rather noisy time delay distribution (solid line) that even extends beyond the actual grating length. The agreement with experimental data is dramatically improved inside the grating region.

Fig. 2 (a) and (b) show that the introduction of phase errors in the central region of the grating has a much larger effect on the reflectivity and transmissivity of wavelengths around the Bragg wavelength. This can be intuitively explained by considering the effective Fabry-Perot cavity picture. The central sections are surrounded by almost equivalent mirrors, so that maximum fringe visibility and therefore sensitivity to external perturbations are expected. In Fig. 2 (c) and (d) out-of-band propagation is considered and a quasi-periodic perturbation effect, consistent with the considerations in [6], is found. The quasi-periodicity changes with the out-of-band wavelength (not shown here). This implies that localized phase shifts will affect different wavelengths to a different degree. If random phase errors distributions are considered, the longitudinal dependence is averaged and all the wavelengths will be affected in a similar way, obtaining an out-of-band background level of the spectral response [1]. On the contrary, if the phase error distribution

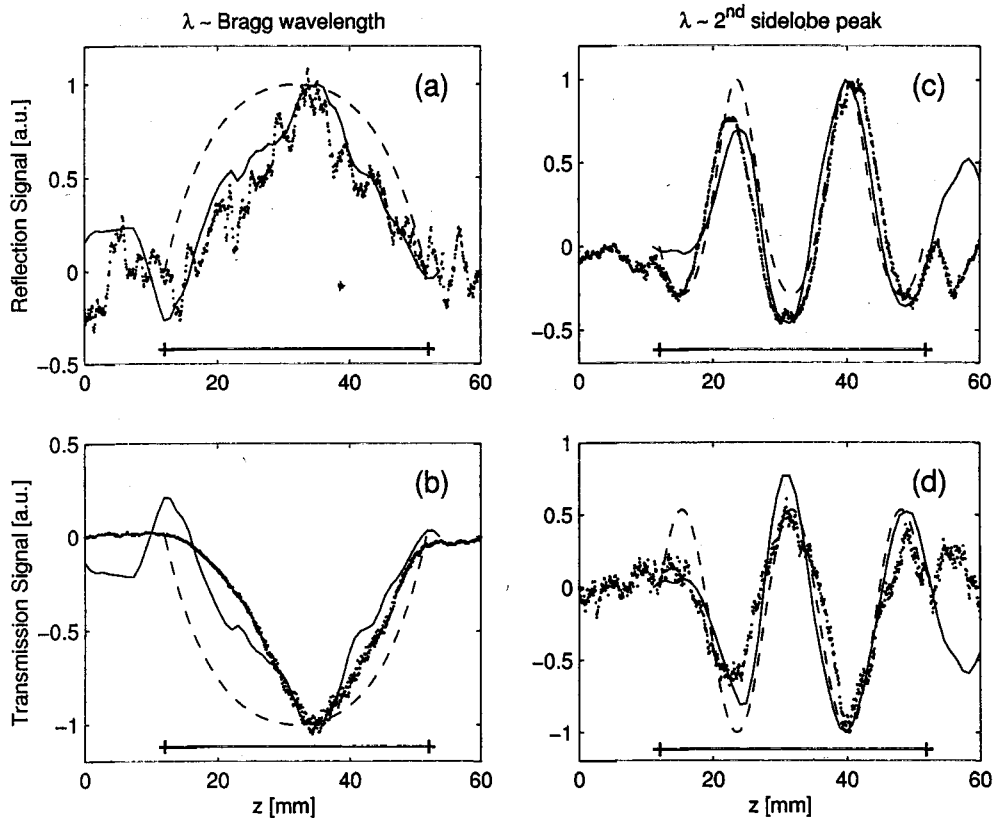


Fig. 2. Comparison between measured data (dotted line) and simulations, both for an ideal uniform grating (dashed line) and the inverse-scattered refractive index profile of the measured grating (solid line). Two different signal wavelengths are shown: inside the band-gap ($\lambda \simeq \lambda_{Bragg}$, left column) and close to the second sidelobe peak ($\lambda \simeq \lambda_{Bragg} + 50$ pm, right column). The reflected signal is shown in the upper row and the transmitted signal in the lower row. All the signals are plotted in normalized units. The actual grating position is marked.

contains a dominant periodicity, maximum variation of the amplitude response is expected at the wavelengths whose $Im\{N(z)\}$ periodicity matches the external perturbation.

In conclusion, the impact of the introduction of phase shifts in different positions along the length of a fiber Bragg grating has been investigated. The theoretical background has been briefly summarized and experimental verification of theory presented. The relation with local time delay in the grating has been stressed, and the effect of phase errors distributions on the final spectral response has been considered. Further work is needed to understand the possibilities of the presented technique for phase errors characterization. The measurement of the real part of the local time delay distribution (the actual time of flight of light in a grating) is beyond the scope of this paper and will be addressed separately.

References

1. R. Feced and M.N. Zervas "Effects of random phase and amplitude errors in optical fiber Bragg gratings," *J. Lightwave Technol.* **18**, pp. 90-100 (1999).
2. J.P. Weber and S. Wang, "Effect of layer thickness variations in a distributed-Bragg-reflector mirror on the phase of the reflected light," *Opt. Lett.* **15**, pp. 526-528 (1990).
3. S.A. Furman and A.V. Tikhonravov, *Basics of optics of multilayer systems*, (Edition Frontieres, 1992), Chap. 1.4.
4. F. Ghiringhelli and M.N. Zervas, "Time delay evolution in Fiber Bragg Gratings," (submitted for publication).
5. J.Y. Lee, H.W. Lee, and J.W. Hahn, "Complex transversal time for optical pulse transmission in a Fabry-Perot cavity," *J. Opt. Soc. Am. B* **17**, pp. 401-406 (2000).
6. E. Brinkmeyer, G. Stolze, and D. Johlen, "Optical space domain reflectometry (OSDR) for determination of strength and chirp distribution along optical fiber gratings," in *Proc. BGPP '97*, paper BSuC2-1, pp. 33-35 (1997).
7. R. Feced, M.N. Zervas, and M.A. Muriel, "An efficient inverse scattering algorithm for the design of nonuniform fiber Bragg gratings," *IEEE J. Quantum Electron.* **35**, pp. 1105-1115 (1999).