

Evolution of Amplitude and Dispersion Spectra during Fiber Bragg Grating Fabrication

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Abstract: An interferometric setup for FBG dispersion measurements is presented which provides high resolution, accuracy and speed. Continuous data recording during FBG fabrication enables a better modeling of the writing process, well-aimed post-processing and active control during fabrication.

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Within the last decade several methods for fiber Bragg grating fabrication by UV illumination have been developed. They work either interferometrically or make use of phase masks and can be distinguished by being full field illumination or scanning techniques. Their degree of sophistication ranges from using a simple arrangement like a Lloyd interferometer or a prefabricated phase mask to highly sophisticated full control scanning schemes to realize prescribed distributions of grating period and strength. In any case, the spectral properties, i.e. reflectivity and dispersion vs. wavelength, of the completed gratings will deviate more or less from simple theoretical predictions and/or goals because of a limited knowledge on UV sensitivity and saturation behaviour of the material (in particular when H₂-loaded), and a limited knowledge on the properties of the UV beam and the writing setup.

In principle, a post-fabrication measurement of the complex reflection factor will yield the actual spatial grating structure via inverse scattering methods (e.g. using the sophisticated layer peeling method [1]) and will, hence, reveal the loci and magnitudes for irregularities that give rise to the observed deviations in the spectral properties. In the case of high quality gratings a procedure like that will not be sufficient due to a limitation of the experimental data accuracy. A much better database can be provided if both dispersion and reflectivity spectra are recorded continuously during the fabrication process. In this case, the grating growth (“vertically” in full field and “longitudinally” in scanning methods) as well as the final structure can be modeled much more accurately. That gives the knowledge to enable post-fabrication trimming procedures or even an active control during the fabrication process.

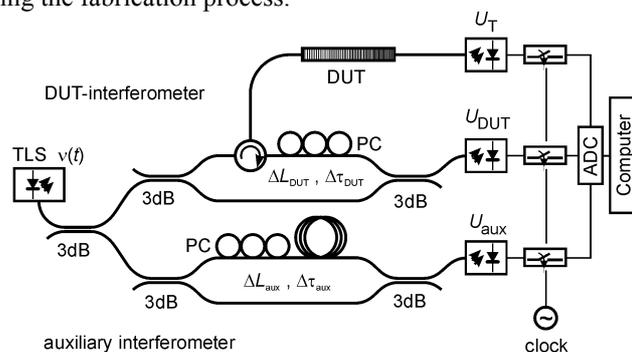


Fig. 1. Measurement setup with DUT- and auxiliary interferometer.

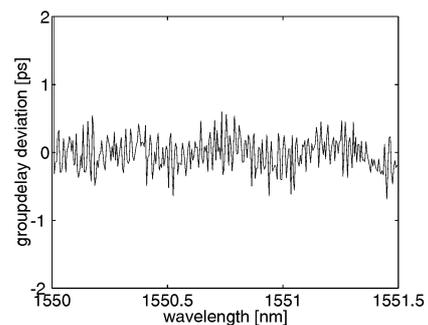


Fig. 2. Measured group delay spectrum of a gold mirror deposited on a fiber end-face (spectral resolution 10 pm).

To be feasible, a procedure like that requires measurement methods with high spectral resolution, high accuracy in group delay and reflectivity measurements, and high speed. These goals can be achieved by using a wavelength scanning interferometric setup as shown in Fig. 1. It consists of two parts which are fed by a common tunable laser source (TLS), an interferometer which contains the grating under test in one of its arms (DUT-interferometer) and an auxiliary unbalanced interferometer with nondispersive arms. A double interferometer arrangement similar to this one was used before for waveguide characterization by coherent optical frequency domain reflectometry (OFDR) [2], and for phase measurements in Bragg gratings [3]. A breakthrough in the latter application was obtained by Froggatt et al. [4], who improved the setup (optical frequency domain characterization, OFDC) and obtained a reduction in measurement speed by a factor of 18,000 with respect to conventional non-interferometric methods. In this paper, we present a further modified

arrangement and we address questions not covered in [4], in particular the role of the tuning characteristics, the spectral resolution and the expected and experimentally measured group delay errors. With the motivation outlined above we use this method for continuous data recording during the fabrication process of Bragg gratings.

Ideally, the instantaneous optical frequency of the laser diode should change linearly with time: $v(t) = v_0 + v' \cdot t$, where $v' = \text{const.}$ and $v'' = 0$. In that case, the auxiliary interferometer is not needed and the desired information on the complex reflection factor $r(v) = |r(v)| \cdot \exp\{j \cdot \phi(v)\}$ is contained in the output detector signal $U_{\text{DUT}}(t)$ of the DUT-interferometer:

$$U_{\text{DUT}}(t) \sim 1 + |r(v)|^2 + 2|r(v)| e^{-j\phi(v)} + 2|r(v)| e^{+j\phi(v)} \quad (1)$$

In the form used in eq.(1) the reference input plane of the DUT is that one where the interferometer is balanced. If a different reference plane is chosen, e.g. the physical location where the grating begins, a linear phase function $2\pi v \Delta L/c$ corresponding to a fixed group delay must be added to ϕ . Fourier transformation $U_{\text{DUT}}(t)$ yields a DC-component and three additional terms: a low frequency term due to the power spectrum $|r(v)|^2$, and two symmetrically located terms at positive and at negative frequencies, respectively. The latter are separated from each other, provided a sufficient fiber delay ΔL_{DUT} (cp. Fig. 1) is used. Eliminating the first and the second term in the Fourier spectrum and performing subsequently an inverse Fourier transform yields the last term in (1), namely $U_{\text{analyt}}(v(t)) = C |r(v)| \cdot \exp\{j \cdot \phi(v)\}$, which contains in particular the information on the group delay spectrum $\tau(v) = (1/2\pi) \cdot d\phi(v)/dv$.

Actually, unavoidable deviations from a linear laser sweep during the measurement will cause appreciable errors in the dispersion measurement. That is the reason for using a nondispersive unbalanced auxiliary interferometer (groupdelay difference $\Delta\tau_{\text{aux}}$) as shown in Fig.1 which can be used in different ways. It will yield a detector signal the AC-part of which varies according to $\cos\{2\pi v(t) \cdot \Delta\tau_{\text{aux}}\}$. In the case of a monotonous wavelength sweep the zero crossings of this signal can be used to generate trigger pulses for data acquisition in the DUT-interferometer that are equidistant in optical frequency (see [4]). In case of a non-monotonous wavelength sweep we replaced the output-coupler of the auxiliary interferometer by a 3x3 coupler. But even with a monotonous wavelength sweep a major drawback of this concept is due to unavoidable electronic propagation times causing the triggered samples to be delayed by a constant value $\delta\tau_{\text{el}}$. The resulting group delay error with a non-linear laser sweep ($v'' \neq 0$) will be $\delta\Delta\tau = \Delta\tau \delta\tau_{\text{el}} v''(t)/v'(t)$. We obtained much better results with respect to group delay errors by sampling the DUT- and auxiliary interferometer equidistant in time with a common clock (see Fig.1). The results are two phase curves $\phi(t)$ and $\phi_{\text{aux}}(t)$ yielding to the group delay of the DUT:

$$\Delta\tau(t) = \Delta\tau_{\text{aux}} \cdot \phi'(t) / \phi'_{\text{aux}}(t), \quad v(t) = v_0 + (1/2\pi\Delta\tau_{\text{aux}}) \phi_{\text{aux}}(t) \quad (2)$$

In our experiments we chose in most cases a mean scanning speed of 5 nm/s and a mean wavelength step size of 0.05 pm (sampling rate 100 kHz) corresponding to 160 ms measurement time and 16,000 data points per 100 GHz ITU-channel. After signal processing we spectrally averaged the group delay data which, of course, leads to noise reduction. With our standard spectral resolution of 10 pm (i.e. average over 200 primary data) we get a relative error in group delay of 10^{-4} and an absolute accuracy of about 1 ps or even below ($\delta\tau_{\text{el}} < 500$ ns). To demonstrate the accuracy of the measurement setup Fig.2 shows the measured group delay of a gold mirror deposited on a 1 m-fiber end-face.

Fig.3a through Fig.3c show three dispersion and transmission spectra out of a long series determined during the writing process of a chirped grating, along with calculated spectra based on a model which takes into account the material properties such as the dependence of UV-induced index vs. fluence including saturation effects, spatial variations of index modulation and average index, as well as writing beam characteristics. The grating fabrication method in this case was a full field Gaussian beam illumination (1/e-diameter = 6 mm, $\lambda = 244$ nm) of the fiber through a chirped phase mask (0.7 nm/cm chirp). The train of measurements make directly visible the well-known fact that a linearly chirped phase mask will not just yield a linear group delay curve in any stage of the writing process. The slope may even have a different sign from that concluded from the phase mask. Fig.3d shows the spectrum of the same grating after post-irradiation by a fringeless Gaussian beam on the long-period side of the grating in order to “flatten” the effective index profile along the grating as it was previously

shown in similar way for a uniform grating in [5]. The local Bragg wavelength changes in this way and the Fabry-Perot resonances disappear.

Thus, one advantage of our online method is that the writing process can be stopped at a point where both the dispersion and the reflectivity curves are “acceptable”. More important, however, this set of data enables a sensitive modeling of the writing process. In particular, it subsequently yields the knowledge on magnitude and loci of deviations from desired spatial grating properties and thereby enables post-processing procedures such as fringeless post-irradiation for effective index correction. On the conference we will also report on respective measurements during grating writing in the scanning mode. Beside getting additional insight into phenomena like group delay ripples and the opportunity for a direct comparison with existing theories [6] this method could also be suitable for active control during the fabrication process.

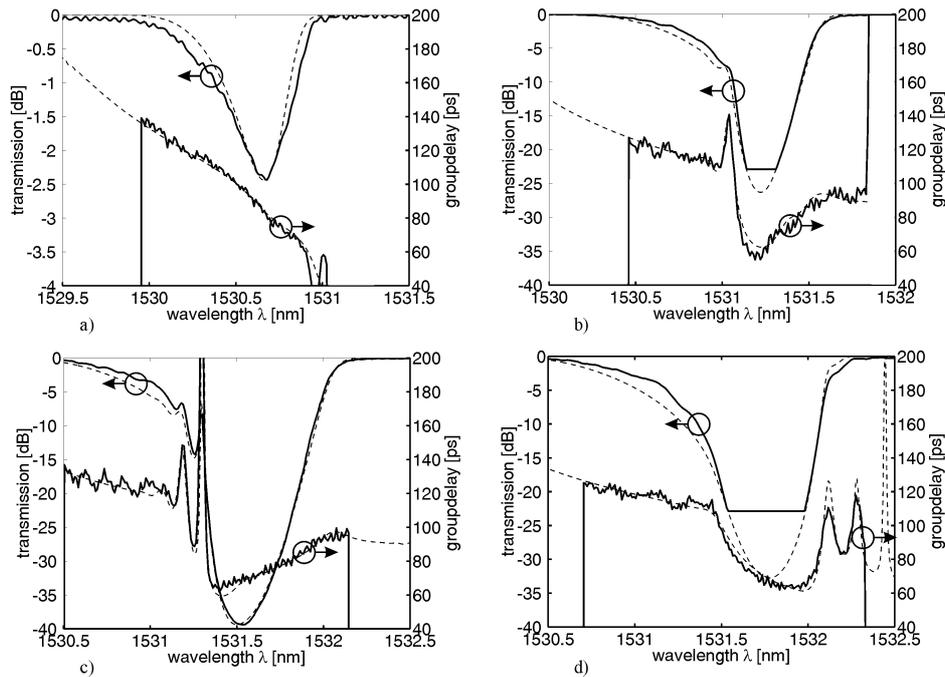


Fig. 3. Transmission spectra and group delay of a chirped Bragg grating during writing process (a-c) and after post-irradiation (d) measurement (—) and simulation (---).

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