Optical comb filter based on spectral Talbot effect in uniform fibre Bragg gratings

N.K. Berger, B. Levit and B. Fischer

A comb optical filter based on the spectral Talbot effect in uniform low reflecting fibre Bragg gratings is numerically and experimentally demonstrated, relaxing the need for any chirp or equivalent phase shifts between the gratings. It can be understood by the analogy between the compression and rate multiplication of phase modulated pulse trains and sampled fibre Bragg grating spectrum formation.

Introduction: In the spatial and temporal Talbot effects, a periodic optical waveform that is modified upon propagation due to spatial or temporal dispersion is recovered after a certain propagation distance, called the Talbot length. An analogous effect was recently shown for the spectrum of chirped fibre Bragg gratings (FBGs) [1]. It is the spectral Talbot effect where the FBG chirp is the counterpart of dispersion. Tuning of the chirp allows one to obtain different spacing between the peaks of comb grating spectra [2]. To achieve an exact analogy to the temporal Talbot effect, the length of each FBG in the spectral case must be very small. Then, the grating chirp affects the phase shift between the gratings rather than the phase variation within the individual gratings. Therefore, chirped sampled FBGs give approximately the same spectral Talbot effect as obtained by uniform FBGs with properly chosen discrete phase shifts between the gratings [3]. This effect was experimentally demonstrated in [4]. In the work described in this Letter, we demonstrate an optical comb filter based on the spectral Talbot effect that is implemented, under certain conditions, using only uniform fibre Bragg gratings without any chirp or equivalent phase shifts between the gratings that correspond to the chirp. We confirm and demonstrate the method, numerically and experimentally.

The spatial refractive index envelope of a FBG structure and the grating reflection spectrum for low grating reflectivities are related by a Fourier transform. This relationship was used for obtaining a comb filter with a square envelope by writing sinc-like individual FBGs [5]. Analogously, the spectrum of an optical pulse and the pulse shape are also related by a Fourier transform. For periodic pulses and periodically spaced (sampled) FBGs, the spatial profile of uniform FBGs corresponds in this analogy to the pulse spectral lines. It should be noted that this analogy is valid for very short gratings. The addition of a chirp to sampled FBGs is equivalent to propagation of a periodic pulse train through a dispersive delay line [1]. We can therefore conclude that, if the spatial envelope of the grating refractive index and the pulse spectrum are identical, then the form of the individual peak in the grating comb spectrum and the pulse shape will also be identical.

For low reflecting short uniform sampled FBGs, we can approximately write the field reflectivity as

$$r(k) = \sum_{s=-N}^{N} r_s(k) \exp[2i(s+N)knL] \tag{1}$$

where $k = 2\pi/\lambda$ is the wavenumber, λ is the wavelength, r_s is the complex field reflectivity of the sth grating, n is the effective refractive index, L is the distance between the sampled FBGs, and $2N+1$ is the number of the gratings. We neglect in (1) multiple reflections between the gratings. On the other hand, the field of periodic optical pulses can be represented as a Fourier series:

$$E(t) = \sum_{s=-Q}^{Q} F_s \exp(is\omega_m t) \tag{2}$$

where F_s is the complex Fourier coefficients, ω_m is the frequency space between the spectral lines (modulation frequency), and $2Q+1$ is the number of the pulse harmonics. From comparison between (1) and (2) we can see that the aforementioned analogy exists if the individual grating spectra $r_m(k)$ does not depend on — or varies very slowly with — the wavelength. This condition is met for very short gratings. The propagation of the pulse in a dispersive medium adds to the discrete spectrum F_s in (2) a phase φ_s. According to the analogy, it corresponds to adding the phase φ_s to the complex reflectivity r_s in (1). It means that there is no necessity for a chirp in the sampled FBGs to implement the spectral Talbot effect. It is sufficient to add to each uniform grating the needed reflection phase φ_s. Moreover, the effect, which we demonstrate here, does not require even those additional phases.

Numerical simulations: We consider the analogy between the compression of phase modulated pulses and the formation of a FBG spectrum. In particular, for temporal sinusoidal phase modulation of continuous-wave (CW) light, the discrete spectrum is expressed as $F_s \propto J_s(A)$ where $J_s(A)$ is the Bessel function of the first kind and A is the modulation index. We calculated the spectrum of 21 uniform FBGs with a length of 0.3 mm and a spacing of 1.018 mm. The modulation of the refractive index of the sth grating was taken to be in the form of $\delta n_s \propto J_s(A)$, $A = 3.1$ rad. The central grating had reflectivity of 1.3%. The calculated spectrum and the reflection phase are shown in Fig. 1. In contrast to temporal phase modulation, the spectrum in the case of 'spectral phase modulation' is not constant, but represents the spectrum of an individual FBG. The spectral phase is slightly different from pure sinusoidal function as shown in Fig. 1. Sinusoidally phase modulated CW light can be transformed to compressed pulses after propagation through a line with a properly chosen dispersion. Analogously, a comb-like spectrum can be obtained from the spectrum shown in Fig. 1 after adding to each sth grating the reflection phase $\varphi_s = Cs^2L^2/2$ where C is the chirp of the equivalent chirped FBGs. It was numerically found that the spectrum can be optimally 'compressed' by chirped gratings for $C = C_{opt} = 379\,306\ \mathrm{m}^{-2}$. The calculated spectrum of the same uniform 21 FBGs with the added reflection phases φ_s for $C = C_{opt}$ is shown in Fig. 2.

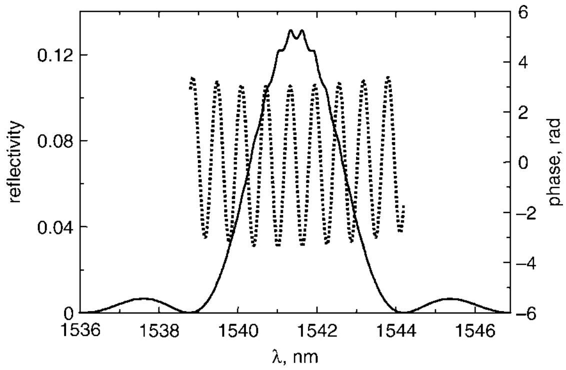

Fig. 1 *Calculated spectrum and spectral phase of 21 uniform FBGs*

—— spectrum
...... spectral phase

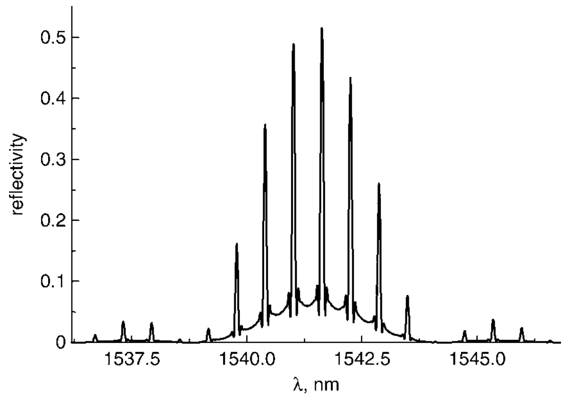

Fig. 2 *Calculated spectrum of same 21 uniform FBGs as in Fig. 1 with added reflection phases* φ_s

Filter implementation and experimental results: It was shown in [6] that, for periodic pulse compression, propagation in a dispersive element can be replaced by pulse rate multiplication by M chosen from the condition that the distance (dispersion) in which the pulse would be optimally compressed must be equal to an integer (or fractional) Talbot length for a new frequency Mf_m. The grating chirp corresponding to the fractional Talbot length in the temporal case [6] can be written by analogy as $C_{fT} = (m/p)(4\pi/L^2)$, where m and p are integers with no common factor ($p = 1$ corresponds to the integer Talbot effect). For the spectrum shown in Fig. 1, multiplication by M is simply performed by writing only every Mth grating from 21 FBGs. Thus, the condition of 'spectral compression' (comb spectrum) without any added discrete phase is: $C_{opt} = C_{fT}$ where L in the equation for C_{fT} is replaced by $M L$. In the experiment, we chose $M = 4$, the grating spacing $M L = 3.952$ mm, $m = 1$, $p = 2$. The FBGs were fabricated by UV laser ($\lambda = 244$ nm) radiation through a phase mask. The reflectivity magnitude and reflection phase of each grating were controlled by a method similar to that described in [7]. The length of each grating was 0.3 mm. The calculated and measured spectrum of the comb filter are shown in Figs. 3 and 4, respectively. Note that, after multiplication and spectral interference between the peaks, the wings in the spectral peaks (Fig. 2) disappear and the reflectivity minimum reaches zero (Figs. 2 and 3).

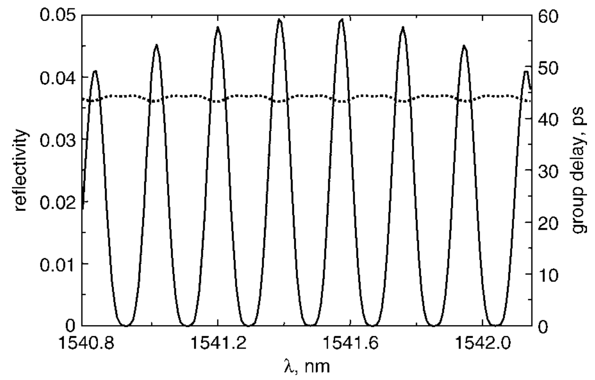

Fig. 3 *Calculated spectrum and group delay of comb filter*

—— spectrum
. . . . . . group delay

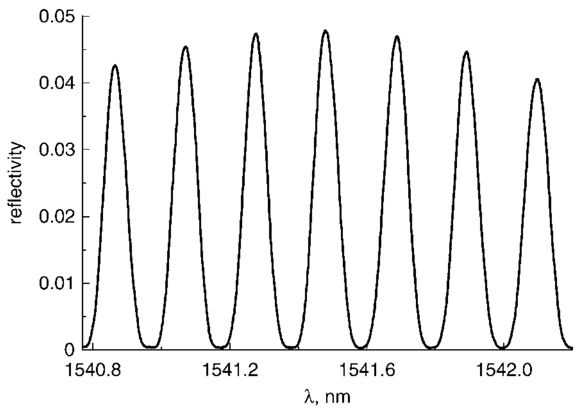

Fig. 4 *Measured spectrum of comb filter*

Conclusion: Our comb filter can also be implemented by using waveguides with $1 \times M$ splitter and $M \times 1$ combiner, and a constant path length difference between the waveguide channels [6] instead of uniform FBGs. Each channel ought to include a phase shifter and an attenuator. The system can be made programmable allowing variations of the individual spectral peaks and their spacing. Another advantage is that the low reflectivity requirement for the FBG is relaxed and there is no limitation on the transmittance of each channel. In addition, the overall comb bandwidth can be significantly broadened compared to the limited value (shown in Figs. 2–4) for the FBGs system, determined by the grating length.

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