Multi-Harmonic Bragg Gratings

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Abstract

Multi-harmonic Fibre Bragg Gratings have been demonstrated experimentally and studied in detail theoretically showing complex reflection response and band-gap disappearance.

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Introduction

During the last decade, fiber and waveguide Bragg Gratings (BGs) have been studied extensively both theoretically and experimentally and have found widespread use in the field of optoelectronics. A number of different techniques have been developed for writing high quality BGs in various waveguide geometries. Regardless of their implementation details, modern grating writing techniques can be broadly divided into two main categories, namely *holographic* and *phase-mask* based ones. The former rely on an interferometric set-up, while the latter make use of a phase mask, to create a periodic UV-light intensity pattern which is subsequently used to expose and perturb the core of the adjacent waveguide.

So far, the vast majority of the standard-grating analyses have only considered simple, single-period (Λ), sinusoidal refractive-index variations [1]. These studies have being concentrating primarily on the grating response at the fundamental ($\lambda=\lambda_B=2n_{eff}\Lambda$) or the Nth-order ($\lambda=\lambda_B/N$) Bragg resonance alone. There have also been a number of studies, pertinent to gratings with non-sinusoidal periodic refractive index perturbations, where, in addition to the fundamental period (Λ), a number of higher spatial-frequency (i.e., $\Lambda/2$, $\Lambda/3$, etc) Fourier components have been considered [2]. In all these cases, however, the grating response at the Bragg wavelength is primarily due to and follows closely the refractive-index component corresponding to the fundamental grating period (Λ). The presence of higher spatial-frequency components in this case only gives rise to extra reflection peaks at $\lambda=\lambda_B/2$, $\lambda_B/3$, etc.

There has also been a substantial study of higher-order Bragg coupling and stop-band interactions in multi-periodic media. It has been shown that, in the presence of more than one harmonics, these interactions can affect the grating response at the main Bragg wavelength and can potentially result in interesting components [3]. The simplest case involves a composite refractive index distribution with two components with periods $\Lambda_1=\Lambda$ and $\Lambda_2=2\Lambda$. At the main Bragg wavelength ($\lambda_B=2n_{eff}\Lambda$), the Λ_2 component provides a *second-order Bragg reflection.* (This should not be confused with the grating response at the second-order Fourier component that, as mentioned above, provides reflection at $\lambda_B/2$). When the amplitudes of the two grating components are appropriately chosen, the stop-band at the main Bragg wavelength disappears.

In this paper, we revisit this last topic and study in detail the reflection and transmission characteristics of two-harmonic Bragg gratings. This study has been motivated by the fact that Bragg gratings written with the phase-mask technique are shown, both theoretically [4] and experimentally [5-6], that, in addition to the their main period ($\Lambda_1=\Lambda$), they can exhibit a strong lower-order periodicity ($\Lambda_2=2\Lambda$). The latter corresponds actually to the phase mask periodicity. This periodicity results from the interference between the ±1 diffraction orders and the residual (un-suppressed) zero and ±2 diffraction orders [4].

In this paper, we first show experimental evidence (Fig.1) of the existence of multiple spatial harmonics in fibre Bragg gratings, written by the phase-mask technique. To the best of out knowledge, such double periodicity is directly observed in fibre gratings for the first time. We then investigate theoretically the complex response of dual-periodicity gratings. We show that, in this case, the grating reflectivity varies non-monotonically as the refractive-index modulation increases monotonically remaining always positive. Their response is reminiscent of the type II-A gratings, where the complex reflectivity evolution, however, is attributed to negative-index changes [7-8].

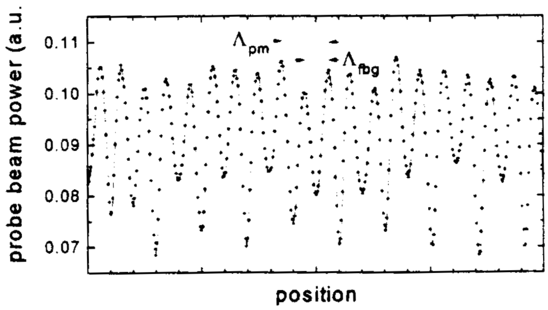

Figure 1: *UV fluorescence power variation along the fibre grating length.*

Dual-periodicity refractive index variation

Figure 1 shows the variation of the fluorescence power of an UV probe beam along a standard fibre Bragg grating, written with the phase-mask technique in a germanium-doped non-hydrogenated fibre. In addition to the expected

FBG period ($\Lambda_1=\Lambda=\Lambda_{rbg}$), the probe power variation shows a marked double-period corresponding to the phase-mask period ($\Lambda_2=2\Lambda=\Lambda_{pm}$). The fluorescence power is proportional to the induced local refractive-index change and, therefore, the variation shown in Figure 1 follows closely the actual refractive index variation. Work is underway to calibrate the UV-fluorescence power and deduce the actual refractive index modulation.

Multi-harmonic Gratings - Theoretical Model

As already mentioned, the grating under consideration, in addition to the fundamental period ($\Lambda_1=\Lambda$), exhibits a strong lower-order periodicity ($\Lambda_2=2\Lambda$). The grating refractive-index variation is expressed as:

$$n(z) \;=\; n_0\left[1+\Delta n_1\cos(K_1 z+\varphi)+\Delta n_2\cos(K_2 z)\right] \qquad (1)$$

where $K_1=2\pi/\Lambda$ and $K_2=K_1/2=\pi/\Lambda$. n_0 is the background refractive index, Δn_1 and Δn_2 (<<1) are the refractive-index modulation amplitudes of the two grating components and φ is their relative spatial phase difference. The reflection and transmission coefficients of such a composite structure can be calculated efficiently either by using the extended coupled-mode theory (ECMT) [3] or an extended transfer-matrix method (ETMM). The latter is known to be an exact approach while the former results after applying the slow-amplitude approximation. We have applied both theories and obtained quite similar results for a wide range of grating parameters.

It is well known that in the presence of a single harmonic only, the grating reflectivity at the main Bragg wavelength (*first-order Bragg reflection*) increases monotonically with Δn. The reflectivity increases as $\tanh^2(\kappa L)$ where $\kappa \propto \Delta n$ is the coupling strength and L is the grating length. The band-gap width, in this case, is proportional to Δn. At the *second-order Bragg reflection*, the grating reflectivity increases as $\tanh^2(\kappa L)$ but now $\kappa \propto \Delta n^2$. It should be also stressed that the reflectivity in this case is in *anti-phase* with respect to the first-order Bragg reflection. The band-gap width is proportional to Δn^2 [3].

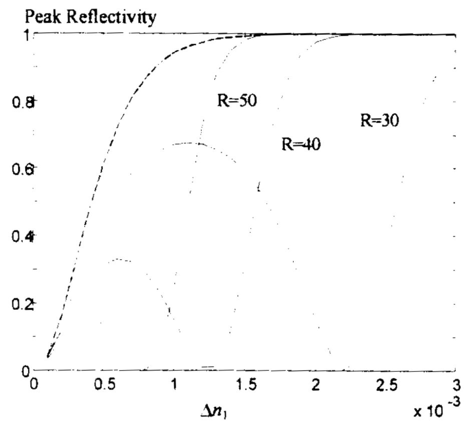

Figure 2: *Total peak reflectivity @1500nm of a two-harmonic grating as a function of Δn_1 for three different ratios r and $\varphi=0$. The dashed line corresponds to the grating peak reflectivity due to Δn_1 alone.*

In the case of multi-harmonic periodicities, the grating response can be altered significantly [3]. For the refractive index variation of Equation (1), at the main Bragg wavelength ($\lambda_B=2n_0\Lambda$), the Δn_1 component contributes with a first-order Bragg reflection, while the Δn_2 component contributes with a second-order Bragg reflection. As mentioned before, these components are in anti-phase and the total grating response will depend on their relative strengths, as well as, their relative phase φ.

Two-harmonic Grating Response

Figure 2 shows the total peak reflectivity of a two-harmonic grating [Eqn. (1)] as a function of the index modulation amplitude of the first component Δn_1. The index modulation amplitude of the second component Δn_2 is proportionally increased so that, for each solid curve, the ratio r ($=\Delta n_2/\Delta n_1$) is constant. The phase shift $\varphi=0$. The dotted line shows the monotonic reflectivity increase due to the Δn_1 component alone. The grating length is 1mm, the period $\Lambda=500$nm and $n_0=1.5$. The main Bragg peak is at $\lambda_B=1500$nm.

It is shown that in contrast with the standard single-harmonic gratings, composite two-harmonic gratings exhibit a complex peak-reflectivity evolution as the index modulation increases. For each ratio r, after an initial increase, the peak reflectivity reaches a local maximum and subsequently decreases to zero. At this point the grating disappears completely. Increasing the modulation index further results in a grating re-appearance with a monotonically increasing reflectivity. This complex total grating response can be understood by considering the partial contributions of the Δn_1 and Δn_2 components. It is shown that, at the initial stage, the reflectivity evolution is dominated by the Δn_1 component (*first-order Bragg reflection*). At the local reflectivity maximum, the contribution of the Δn_2 component (*second-order Bragg reflection*) becomes comparable to the first-order one. As mentioned before, the first- and second-order Bragg reflections are in anti-phase and, therefore, counteract each other. At the zero-reflection point, the two partial reflectivities have exactly the same amplitude and cancel each other completely. For larger index modulations, the second-order Bragg reflection (due to Δn_2) dominates and the grating reflectivity increases monotonically. It is worth mentioning that in this last stage, assuming that the background refractive index n_0 remains constant, the peak reflectivity shifts towards shorter wavelengths. This effect can be explained by the accompanied apparent phase velocity increase [3]. It has been shown analytically (using ECMT) and confirmed numerically (using ETMM) that the dual-periodicity grating reflectivity can always go to zero when the two index modulation amplitudes satisfy:

$$\Delta n_1 = (1/2)\Delta n_2^2$$

The interaction of the two grating components is further investigated by varying their relative spatial phase φ. Figure 3 shows the total peak reflectivity as a function of the index modulation for different φ and $r = 35$. It is shown that when $\varphi \neq 0$ the perfect destructive interference is perturbed and the peak reflectivity *does not* go to zero. For $\varphi = \pi$, constructive interference between the two partial reflections takes place for all index modulations resulting in a very strong monotonically increasing reflectivity.

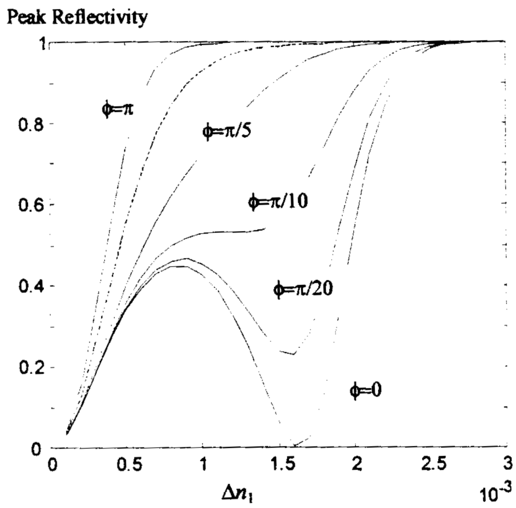

Figure 3: *Total peak reflectivity @1500nm of a two-harmonic grating as a function of Δn_1 for different relative phase shifts φ and $r=35$. The dashed line corresponds to the grating peak reflectivity due to Δn_1 alone.*

Discussion - Conclusions

By measuring the UV fluorescence power of a probe beam, we have, for the first time, shown strong evidence of dual periodicity in gratings fabricated by the phase-mask technique in germanium-doped non-hydrogenated fibres. We have studied the reflectivity evolution of such *dual-periodicity positive-index gratings* and have found striking performance similarities with type II-A (negative-index) gratings. However, in contrast with the negative-index type II-A gratings, the complex behaviour in the dual-periodicity gratings is due to a first- and second-order reflection interference effect.

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