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Multi-TBaud Optical Coding Based on Superluminal Space-to-Time Mapping in Long Period Gratings

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ABSTRACT

A novel time-domain ultra-fast pulse shaping approach for multi-TBaud serial optical communication signal (e.g. QPSK and 16-QAM) generation based on the first-order Born approximation in feasible all-fiber long-period gratings is proposed and numerically demonstrated.

Keywords: Pulse Shaping; Fiber Optics Components; All-optical Devices; Ultra-fast Processing

1. Introduction

Fiber and integrated-waveguide grating structures have been widely investigated for ultrafast optical pulse shaping and processing applications, including generation and detection of high-speed complex data streams in telecommunication systems [1,2]. The advantages of these solutions are associated with their intrinsic compact, low-loss all-fiber/waveguide implementations, e.g. in contrast to widely used programmable linear waveshapers based on bulk-optics configurations (involving diffraction gratings and spatial modulators) [3]. In particular, there has been an important body of work on the use of short-period (Bragg) fiber/waveguide gratings (BGs) for ultrafast optical coding, namely generation of customized temporal optical data streams under different amplitude and/or phase coding schemes [1,2]. These solutions are particularly interesting for applications requiring the generation of time-limited data streams (composed of a few consecutive symbols), such as for optical code-division multiple access (OCDMA) and optical label-switching communications [1,2]. Long-period fiber gratings (LPGs) have recently attracted a great deal of interest for linear optical pulse shaping and processing applications [4]. However, to date, there are very few published works on their potential for general optical coding operations; some interesting LPG designs have been recently reported [5] but they are limited to the synthesis of temporally symmetric, binary intensity-only (on-off-keying, OOK) optical codes.

As a general rule, in optical grating-based linear filters, to achieve a faster temporal signal, a smaller spatial feature is required in the coupling-coefficient (grating apodization) profile. Previous studies in counter-directional coupling structures [6,7], e.g. fiber/waveguide BGs, have revealed that under the first-order Born approximation (*i.e.* weak-coupling conditions), the output time-domain optical field complex envelope variation follows the spatial variation of the complex coupling coefficient. This phenomenon, referred to as space-to-time mapping, provides a very straightforward mechanism to synthesize optical waveforms (*e.g.* coded communication data streams) with prescribed complex temporal shapes. However, in BGs, the ratio (v) between the resolution of the mentioned variations in space (Δz) and time (Δt) is necessarily lower than the propagation speed of light in vacuum (c) [8], *i.e.* $v = \Delta z/\Delta t < c$, (see the case of BG in **Figure 2** and the given numerical example in **Table 1**). Considering a typical achievable sub-mm resolution for fiber grating apodization profiles, fiber BG pulse shapers/ coders are thus limited to resolutions of at least several picoseconds [1,2,7].

This work focuses on the use of the first-order Born approximation in co-directional coupling filters, particularly LPGs. As illustrated in **Figure 1(a)**, similarly to the case of BGs [6,7], under weak-coupling conditions, the grating complex (amplitude and phase) apodization profile can be directly mapped into the LPG filter's temporal impulse response [8,9]. In contrast to the BG case, the space-to-time mapping speed ($v = \Delta z/\Delta t$) in LPG filters can be made much higher than the propagation speed of light in vacuum. As illustrated in **Figure 2**, this superluminal space-to-time mapping speed in LPGs enables the synthesis of waveforms with temporal features several orders of magnitude faster than those achievable by BGs

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(assuming the same spatial resolution in the grating apodization profile). In this work, we numerically demonstrate the straightforward use of this phenomenon for ultra-fast optical coding applications, particularly for generation of customized serial optical communication streams under any desired complex coding format (*e.g.* QPSK and 16-QAM modulation formats in the examples reported here), well in the TBaud range (femtosecond resolutions) using readily feasible LPG designs, *e.g.* with grating apodization resolutions above the millimeter range.

2. Theory of Superluminal Space-to-Time Mapping in LPGs

Our theoretical derivations on the superluminal space-to-time mapping phenomenon in LPGs rely on the standard coupled-mode equations for the case of co-directional coupling. The mathematical details of these derivations will be reported elsewhere [9].

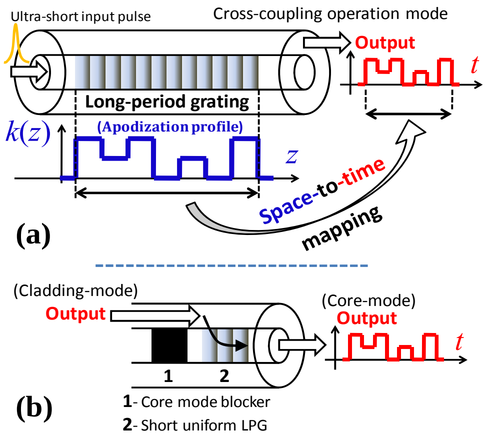

Figure 1. (a) Schematic of the proposed ultra-fast pulse shaping/coding approach based on superluminal space-to-time mapping in LPGs; (b) Illustration of a previously demonstrated fiber-optic approach [4] to transfer the cross-coupling signal from the fiber cladding-mode into the fiber core-mode by concatenating (1) a core-mode blocker and (2) a short, strong uniform LPG.

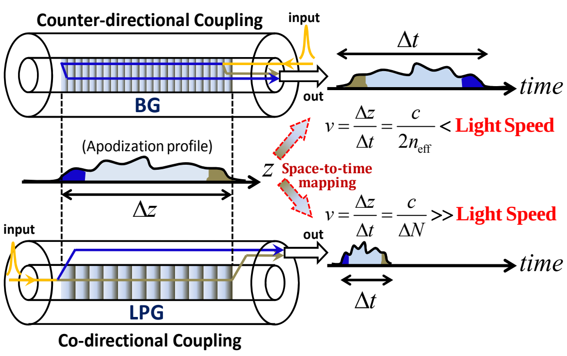

Figure 2. Comparison of the two pulse shaping approaches based on space-to-time mapping in fiber BGs and LPGs.

The LPG coupling coefficient (apodization) profile, i.e. $k(z)$ in **Figure 1**, is a complex function defined as $k(z) = |k(z)|\exp[j\varphi(z)]$. The magnitude $|k(z)|$ depends on the amplitude of the refractive index modulation along the LPG length, as illustrated in **Figure 3**. The grating discrete phase-shifts and grating period changes along the LPG length are accounted for in the phase term of the coupling coefficient, *i.e.* $\varphi(z)$. Some single phase-shifted gratings are also illustrated in **Figure 3** aimed to induce the corresponding discrete jumps in the phase of the coupling coefficient profile, *i.e.* $\varphi(z)$. Our theoretical studies [8,9] have shown that under weak-coupling strength conditions (*i.e.* strictly, cross-coupling power spectral response peak < 10%), the complex envelope of the temporal impulse response (let us call it $h(t)$) of the cross-coupling transfer function, *i.e.* core-to-cladding transfer function in fiber LPGs, is approximately proportional to the variation of the complex coupling coefficient $k(z)$, as a function of the grating length z after a suitable space-to-time scaling [8,9]. In particular, the space-to-time mapping speed (v), is obtained as $v = c/\Delta N$, where $\Delta N = (n_{\text{eff1}} - n_{\text{eff2}})$, and n_{eff1} and n_{eff2} are the effective refractive indices of the two coupled-modes around the wavelength of interest. Mathematically,

$$h(t) \propto \left\{ |k(z)| e^{j\varphi(z)} \right\}_{z=t\cdot c/\Delta N} \qquad (1)$$

Clearly, ΔN can be designed to be much smaller than 1, and consequently the resulting speed (v) can be made significantly higher than the speed of light in vacuum. This superluminal space-to-time mapping speed is also significantly higher than the corresponding (subluminal) speed in the case of BG devices, *i.e.* $v = c/(2n_{\text{eff}})$, where n_{eff} is the average effective refractive index of the propagating mode in the grating, see the comparison in **Figure 2**. This is the key to design optical pulse shapers (*e.g.* coders) based on LPGs with impulse responses having several orders of magnitude faster temporal features than their counter-directional filter counterparts (BGs).

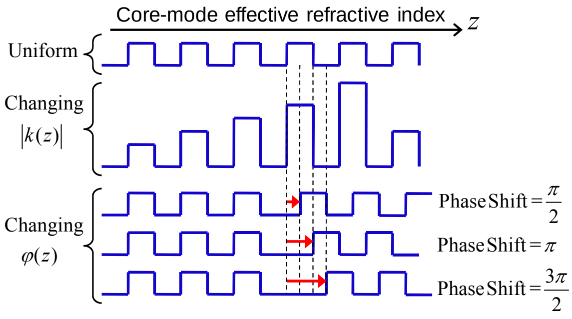

Figure 3. Illustration of variations on the amplitude and phase of the coupling coefficient profile, *i.e.* $|k(z)|$ and $\varphi(z)$ respectively, along the LPG length. For the phase change examples, some single phase-shifted gratings to generate the corresponding discrete jumps in $\varphi(z)$ are illustrated.

Notice that the LPG's cross-coupling operation mode can be practically implemented based on either integrated- waveguide technology (by simply inducing the coupling between two physically separated waveguides [10]) or a fiber-optic approach [4]. **Figure 1(b)** shows a schematic of a previously demonstrated all-fiber approach for implementation of the cross-coupling operation mode in LPGs [4], *i.e.* to ensure that both the input and output signals are carried by the fiber core mode. A core-mode blocker and a short broadband uniform LPG can be used for undistorted transference of the desired output signal from the cladding mode into the core mode. designations.

3. Numerical Comparison between BG-Based and LPG-Based Pulse Coders

Let us assume a fiber BG working in reflection and a fiber LPG working in the cross-coupling operation mode, both made in standard single-mode fiber (Corning SMF28), see **Figure 4**. The grating period for the LPG is assumed to be Λ = 430 μm, which corresponds to coupling of the fundamental core mode into the LP06 cladding mode at a central wavelength of 1550 nm. The BG has a period of 528 nm, corresponding to a Bragg wavelength of 1550nm. The average effective refractive index of the propagating mode in the BG is $n_{\text{eff}} = 1.4684$ and for the LPG: $n_{\text{eff1}} = 1.4684$ and $n_{\text{eff2}} = 1.4648$ [11-13]. **Table 1** shows the estimated space-to-time mapping speeds for these two examples. Let us further assume that the two considered BG and LPG devices have the same length of 10cm and they are both identically spatially-apodized for a target optical OOK bit stream pattern generation, as shown in **Figure 4**.

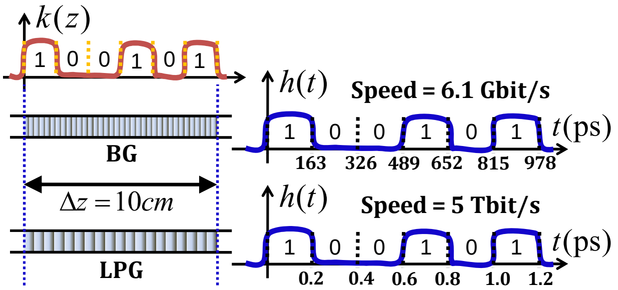

Figure 4. Comparison of the two OOK pulse-coding approaches based on space-to-time mapping in BGs and LPGs.

Table 1. The estimated space-to-time mapping speed for the considered BG and LPG made in SMF28 fiber.

	Space-to-time mapping speed
BG	$V = c/(2\,n_{\text{eff}}) = 1.022 \times 10^8$ (m/s)
LPG	$V = c/(n_{\text{eff1}} - n_{\text{eff2}}) = 833.3 \times 10^8$ (m/s)

In both cases, the amount of peak coupling coefficient is assumed to be low enough to satisfy weak-coupling conditions. Based on the space-to-time mapping theory, by launching an ultra-short optical pulse into the considered optical filters, the target bit stream patterns (*i.e.* $h(t)$ in **Figure 4**) will be generated at the filters' output port. As expected from the different space-to-time mapping speeds, the bit rate of the generated bit stream pattern by the LPG device should be nearly 1,000 faster than that generated by the BG filter.

4. Numerical Simulations

Using coupled-mode theory combined with a transfer-matrix method [13], we have numerically simulated two different LPG designs for generation of two 8-symbol optical QPSK and 16-QAM signals, each with a speed of 4TBaud (4TBaud), from an input ultra-short optical Gaussian pulse with a (full width at 10% of the peak amplitude) duration of 100 fs. **Figure 5** shows the results of these numerical simulations. The LPG design parameters are those defined above and the input optical pulse is assumed to be centered at the LPG resonance wavelength of 1550 nm. In the numerical simulations, the following wavelength dependence has been assumed for the effective refractive indices of the two interacting (coupled) modes [12]: $n_{\text{eff1}}(\lambda) = 1.4884 - 0.031547\lambda + 0.012023\lambda^2$ for the core-mode and $n_{\text{eff2}}(\lambda) = 1.4806 - 0.025396\lambda + 0.009802\lambda^2$ for the LP06 cladding-mode, where $1.2 < \lambda < 1.7$ is the wavelength variable in μm.

Figsures 5(a) and **(b)** show the designed amplitude and phase grating-apodization profiles for the target QPSK and QAM coding operations, respectively. The grating designs are relatively straightforward and simple, just being spatial-domain mapped versions of the respective targeted complex time-domain optical data streams. In particular, **Figrues 5(g)** and **(h)** show the amplitude and phase profiles of the time-domain waveforms at the outputs of the simulated LPG designs, demonstrating accurate generation of the targeted 4TBaud data streams, as per the coding formats defined in **Figures 5(c)** and **(d)**, respectively, in excellent agreement with the inscribed grating-apodization profiles.

Notice that considering the superluminal space-to-time mapping scaling value in the designed LPG (~833.3 × 10^8 m/s), each symbol time period of 250 fs corresponds to a fairly large spatial period of ~2.07 cm. As anticipated, time resolutions in the femtosecond regime (e.g. for the inter-symbol amplitude transitions and discrete phase jumps) can be achieved based on readily feasible millimeter grating spatial resolutions. The spectral responses of the two designed LPG filters are shown in **Figures 5(e)** and **(f)**, respectively. It is worth noting the intrinsic complexity of these responses (also for the phase, not shown here), which would make it very challenging for implementation using a frequency-based optical filter design approach, *e.g.* such as using conventional programmable linear wave-shapers.

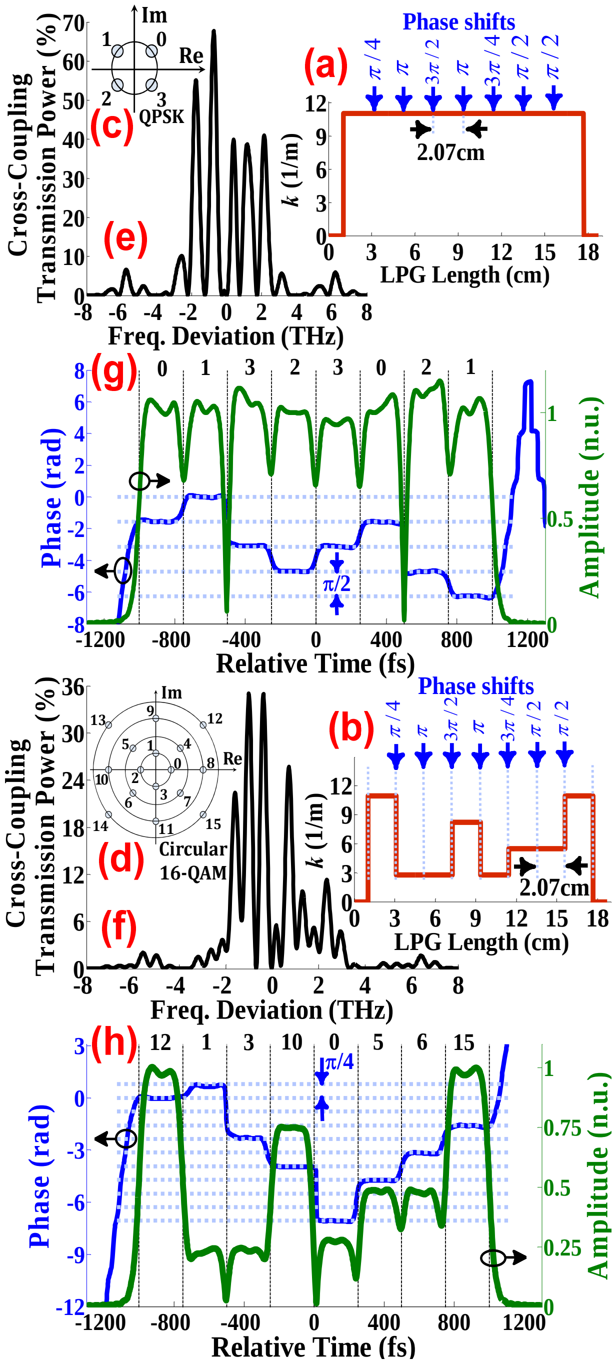

Figure 5. Simulation results of the two designed LPGs (a,b) to generate 8-symbol optical QPSK (c) and 16-QAM (d) data stream patterns, *i.e.* "0"1"3"2"3"0"2"1" and "12"1"3" 10"0"5"6"15" respectively, with a speed of 4TBaud from an input (full width at 10% of the peak amplitude) 100fs optical Gaussian pulse. (*e,f*) The corresponding spectral power responses of the designed LPGs. (*g,h*) The corresponding output temporal amplitude and phase responses.

5. Conclusions

We have proposed and numerically demonstrated a novel time-domain pulse shaping approach for synthesizing THz-bandwidth linear optical filters with arbitrary ultrafast temporal impulse responses based on the first-order Born approximation in LPGs. The proposed technique is particularly useful for generation of multi-TBaud serial optical communication data streams under complex (PSK, QAM *etc.*) coding formats using readily feasible and simple LPG designs, *e.g.* with spatial resolutions above the millimeter range. The corresponding matched-filtering devices for efficient decoding and detection of the generated data streams could be also designed and implemented using this same LPG approach.

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