Waveguide grating spectral phase-shifter for temporal femtosecond pulse splitting

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Abstract
A waveguide grating based on a mirror causes a 2π phaseshift of controllable slope in the spectrum of a femtosecond pulse giving rise to an adjustable, lossless temporal pulse splitting. A representation of resonant reflection based on phenomenological parameters enables the designer to achieve the synthesis of the mirrored waveguide grating structure exhibiting the desired temporal pulse shape. The example of a temporal beam splitter under fabrication is presented. Experimental results will be presented at the conference.

1. Introduction

The present paper concerns the technique of temporal femtosecond pulse shaping by acting on the spectral phase of the pulse by means of a waveguide grating mirror. The desired wavelength-dependent phaseshift Φ(λ) is imprinted on the spectrum of a pulse by a resonant grating composed of a slab waveguide of corrugated surface exhibiting the effect of 100% resonant reflection [1]. Usually this wavelength, angularly and polarization selective effect is used for its sharp high reflection peak. The sudden phase change associated with the reflection modulus peak is generally discarded except in [2] where it is shown that the phase variation is of utmost importance when such resonant mirror is associated with another element or inserted into a system. This is precisely the case in the present application where the spectral phase only, not the modulus, is the matter of concern. We propose here a lossless pulse shaping element using a mirror-based waveguide grating as a phase-only modulator. The experimental test of the element under fabrication will be reported at the conference.

2. The spectral phase of resonant reflection and its temporal transform

The temporal profile $f_f(t)$ of a pulse of initial spectrum $F_i(\nu)$, after experiencing a lossless frequency dependent phaseshift φ(ν), is given by the Fourier transform of the product $F_i(\nu)\exp[j\varphi(\nu)]$. It will be shown hereunder that the spectral phase of the resonant reflection from a mirrored slab waveguide grating is simply and remarkably given by an arctangent function of 2π amplitude :

$$\varphi(\nu) = -2\arctan\left(b(\nu-\nu_0)\right) \qquad (1)$$

where ν is the optical frequency, ν_0 is the optical frequency for synchronous waveguide excitation, $b = \frac{2\pi \sin\theta_i}{c\alpha}$ is the phase slope coefficient, θ_i is the incidence angle on the corrugated slab and α is the radiation coefficient [3]. Calculating the inverse Fourier transform of the product of a Gaussian initial pulse of half-width duration Δt by the spectral phase of expression (1) yields the temporal shape of the reflected pulse analytically :

$$f_f(t) = \frac{\sqrt{2\pi^3}\Delta t}{\sqrt{\ln 2}b} e^{\left(\frac{\pi\Delta t}{\sqrt{2\ln 2}b}\right)^2} e^{-\frac{2\pi}{b}t}\left[1+erf\left(\frac{\sqrt{2\ln 2}}{\Delta t}t-\frac{\pi\Delta t}{\sqrt{2\ln 2}b}\right)\right]-e^{-\frac{2.\ln 2}{\Delta t^2}t^2} \qquad (2)$$

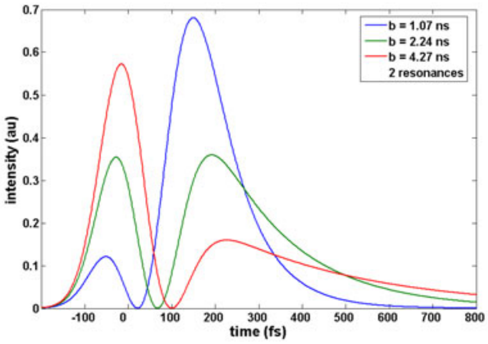

Fig. 1: Examples of temporal profiles obtained by introducing an arctangent phase in the spectrum of a 130 fs input pulse for different values of phase slope b.

Figure 1 illustrates the temporal shape of the output pulse obtained with the analytical expression (2) assuming a Gaussian input pulse of 130 fs half-width. The initial pulse is split into two subpulses. ν_0 sets the location of the phase change in the spectrum of the pulse. The slope b which depends on the resonance width defines the balance between the two subpulses. For instance, for a femtosecond pulse centered at 800 nm wavelength, the dimensionless ratio b/Δt should be comprised between essentially 6 and 55 to ensure a 10 % minimal subpulse intensity ratio. The temporal spacing between the two subpulses is mainly determined by the amplitude of the phase jump. It is an intrinsic limitation of resonant grating waveguide reflection to exhibit no more than 2π phase shift. However, there are ways to increase it by tailoring the dispersion of the slab waveguide for instance; this is beyond the scope of the present paper.

3. Modulus and phase of the reflection of a grating waveguide

A vivid representation of the reflection across a waveguide mode resonance will now be presented to give some insight into the operation of the element.

Figure 2 is the sketch of a waveguide grating slab propagating a guided mode excited contra-directionally by a femtosecond beam by means of the –1st order of the grating. Under collinear incidence and θ_i incidence angle, the resonance condition is $k_0n^*+\beta = K_g$ where $k_0n^* = k_0\sin\theta_i$, $\beta = n_ek_0$ and $K_g = 2\pi/\Lambda$ where Λ is the grating period. The excitation of the waveguide mode is made collinearly via the –1st diffraction order for sake of preventing radiation losses via other orders. n_e is the effective index of the excited mode.

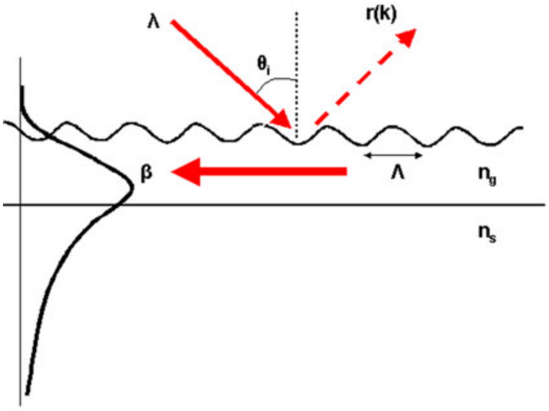

Fig. 2: Contradirectional coupling configuration of a plane wave under incidence angle θ_i into a grating waveguide via the –1st order. n_s and n_g are the refractive indices of the substrate and the waveguide media respectively.

In the inhomogeneous problem representation the occurrence of grating mode excitation is expressed as a pole of the reflection function. The reflection around the resonance can be expressed as the sum of two terms : an essentially constant regular term r_0 and a term r_g resulting from the presence of the pole in the k-vector space [4] :

$$r(k) = r_0 + r_g(k) \qquad (3)$$

$r_g(k)$ is the part of the reflection due to the re-radiated guided-wave :

$$r_g(k) = \frac{a_p}{(k-\beta) - j\alpha} \qquad (4)$$

where a_p is a complex constant.

The reflection coefficient r(k) is a complex function of the real variable k expressed as k_0n^*-K_g. The scan of k will be made experimentally on the real axis by varying the incidence angle or the period.

$r_g(k)$ is a complex function having a first order pole. Interestingly, the locus of $r_g(k)$ in the complex plane upon the scan of k on the real axis is a circle as illustrated in Figure 3.

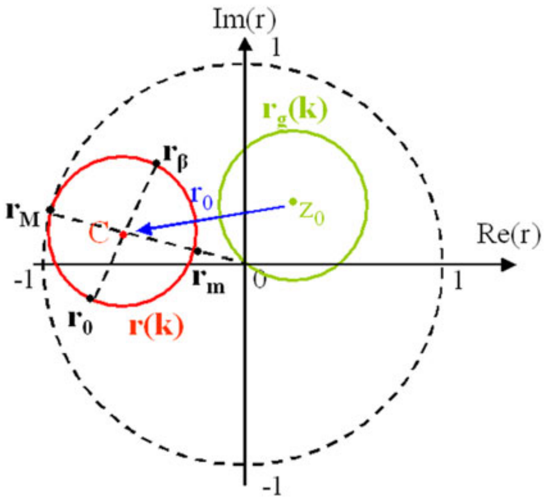

Fig. 3: Representation of the reflection coefficient r(k) in the complex plane.

The circle $r_g(k)$ is centered at complex point $z_0 = ja_p/2\alpha$ and its radius is $|a_p|/2\alpha$. The origin is on the circle since $r_g(k)$ is zero far from the resonance. Upon a scan along k from -∞ to +∞, the r_g apex describes one turn in the clockwise direction.

r(k) is the sum of the regular part r_0 and the resonant part $r_g(k)$. This just amounts to translating the described circle by the complex quantity r_0. Knowing that the reflection modulus is 1 at the condition of resonant reflection $r_M = r(k_M)$, the r(k) circle is tangent at this point to the circle of radius 1 centered at the origin of the complex plane. Therefore, the origin, the r(k) circle center C and the complex unit reflection point r_M are on the same straight line. On the same straight line is also the point of minimum reflection r_m. The r(k) circle is thus centered at point :

$$C = r_0 + j\frac{a_p}{2\alpha} \qquad (5)$$

and its radius is still $R = \dfrac{|a_p|}{2\alpha}$.

4. The phase of reflection in a mirror based resonant grating

The results of the last section are the basis for the design of the present spectral phase shifter for femtosecond pulses. The aim in the present temporal shaping operation is to have the whole spectrum reflected with the phaseshift somewhere in the middle. This condition can simply be achieved by placing the grating waveguide on top of a background mirror with sufficient distance between the waveguide and the mirror to electromagnetically isolate the modal field from the mirror. A thick low index buffer layer will thus be inserted between the waveguide slab and the mirror as sketched in Figure 4.

The change which the base mirror brings in the complex representation of the reflection is strikingly illustrated in Figure 4. The lossless mirror imposes the reflection coefficient modulus to always be 1. Thus the reflectivity circle is the unity circle with its center at the origin of the complex plane. Consequently, setting expression (5) to 0 gives a simple expression for a_p :

$$a_p = 2j\alpha r_0 \qquad (6)$$

Then, using the above expression in the polar function (3) of the reflection coefficient gives :

$$r(k) = r_0\left(1 + \frac{2j\alpha}{(k-\beta) - j\alpha}\right). \qquad (7)$$

Expression (6) is a key result as it relates the unknown constant a_p of the algebraic expression (3) of r(k) to the phenomenological grating waveguide parameter α, and to an experimentally measurable quantity, r_0. As the modulus of r(k), therefore of r_0 is 1, the final expression for r(k) can be written as a phase function :

$$r(k) = -r_0\left(\frac{\left(\alpha - j(k-\beta)\right)^2}{(k-\beta)^2 + \alpha^2}\right) = e^{j\left(\pi + \varphi_0 - 2\arctan\left(\frac{k-\beta}{\alpha}\right)\right)}$$

where φ_0 is the phase of the reflection coefficient off-resonance. Thus, the phase dependence of the reflection on a mirror-based resonant grating is now simply given by :

$$\varphi(k) = \pi + \varphi_0 - 2\arctan\left(\frac{k-\beta}{\alpha}\right) \qquad (8)$$

$$\varphi(\lambda) \simeq \pi + \varphi_0 + 2\arctan\left(\frac{2\pi \sin\theta_i}{\alpha\lambda_0^2}(\lambda - \lambda_0)\right) \qquad (9)$$

The phase of r(k) is now fully defined as a function of the opto-geometrical and phenomenological parameters in the case of a mirror based structure. This is the result expressed in (1) in term of the optical frequency ν which is at the basis of the temporal transform established in section 2.

5. Example of a pulse splitting monolith

An example of waveguide grating structure which is under fabrication is given in figure 4. It consists of an alternation of high index HfO_2 (n_h = 2.06) and low index SiO_2 (n_b = 1.46) layers. The mirror is composed of a gold substrate on which a 6-λ/4-layer dielectric mirror is deposited to increase the total efficiency. Minimizing the modal field at the metallic interface by inserting a low index buffer layer permits to decrease losses in the neighbourhood of the resonance. A 400 nm pitch grating of 60 nm depth will be etched in the last high index layer.

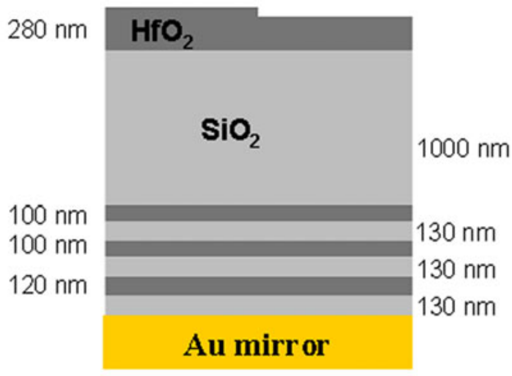

Fig. 4: Structure under fabrication.

Experimentally, the femtosecond incident beam at 800 nm wavelength is polarized horizontally. Therefore the structure is optimised to be excited by a TM polarized beam. Numerical simulations giving the spectral phase and the temporal profile of the output pulse are presented in figure 5 and figure 6. A first 105 fs width pulse containing 30% of the output energy is expected to be followed by a 225 fs pulse containing 70% of the energy.

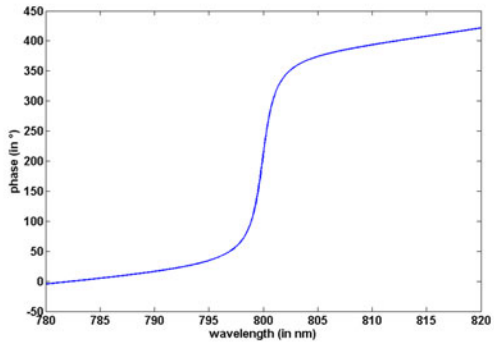

Fig. 5: Spectral phase induced by the model structure.

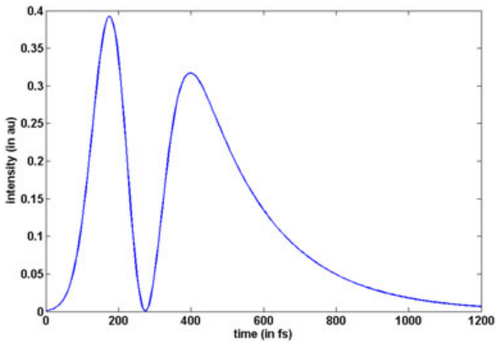

Fig. 6: Temporal profile of the output pulse after reflection of a 130 fs gaussian pulse on the resonant grating.

The multilayer structure has been fabricated on top of a gold mirror. The 400 nm period corrugation grating is under printing, and RIBE transfer in the last HfO_2 layer will be shortly performed. The functional demonstration under femtosecond pulse incidence will be reported at the conference.

7. Conclusion

A graphic representation of resonant reflection from a waveguide grating gives a vivid physical insight in the operation of a monolithic spectral phase modulator allowing the temporal shaping of femtosecond pulses. The association of a resonant waveguide grating mirror with a high reflectivity wide band mirror next to the latter represents a pure phaseshifting element where all spectral components of the pulse experience 100% reflection in modulus. The resulting 2π phase shift in the form of an arctangent function of the optical frequency gives rise to an effect of temporal pulse splitting. The relative amplitude of the subpulses can be chosen by adjusting the radiation coefficient α of the grating waveguide which determines the slope of the phase variation. This effect can be used in diverse laser machining applications as well as, if the temporal spacing between subpulses can somehow be increased and adjusted, to time resolved spectroscopic applications. Femtosecond pulse splitting using this element, which is now at the final fabrication stage, will be reported at the conference.

8. Acknowledgements

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