Non-sinusoidal phase modulations for improved performance of high power lasers

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Abstract. Spectral broadening is required on high power lasers to avoid Stimulated Brillouin Scattering in the laser chains and to smooth the focal spot. Up to now, spectral broadening has been obtained by sinusoidal phase modulations. However, it leads to non-homogeneous spectra, which is not optimal. In this paper we show that, thanks to non-sinusoidal phase modulations, performance of high power lasers may be enhanced. Furthermore, we demonstrate theoretically and experimentally that adjusting non-sinusoidal phase modulations may be almost as simple as adjusting sinusoidal ones.

1. Anti-Brillouin and smoothing functions for high power lasers

Spectral broadening is required on high power lasers such as National Ignition Facility or the Laser MégaJoule (LMJ) to avoid Stimulated Brillouin Scattering (SBS) in the laser beam lines [1] and to smooth the focal spot [2]. Up to now, spectral broadening has been obtained by a sinusoidal phase modulation. A sinusoidal modulation is defined by its frequency $f_m$ and its amplitude $m_1$ (modulation depth). Our calculations show that for LMJ avoiding SBS at $3\omega$ requires that the maximum of the spectral power distribution (SPD) be below around 6%, with 100% corresponding to a not-broadened spectrum. Current values for LMJ are thus $f_m=2$GHz and $m_1=21$. Smoothing consists of rapidly moving the speckle pattern of the focal spot. It is characterized by the asymptotical contrast that is equal to the RMS value of the spectrum intensity. The smoothing modulation frequency is set by the smoothing grating to 14.25GHz and the modulation depth $m_1$ is set to 15 at $3\omega$ to reach an asymptotical contrast of 22%.

However, sinusoidal modulations lead to non-homogeneous spectra, as can be seen in the left part of Figure 1. Hence, to reach a given performance, a higher broadening is required. The bandpass of a laser beam line is theoretically limited by the spectral acceptance of the frequency conversion in the final optics assembly and in practice also by other imperfections. A high spectral broadening slightly reduces the total energy and leads to temporal shape distortions through so-called FM to AM conversion [3]. Thus, tailoring the spectrum would be welcome [4, 5], for instance to make it flat, to reach the same optical performance with a narrower spectral bandwidth, as shown in the right part of Figure 1.
2. Non-sinusoidal phase modulations

It can be shown that such ideal spectra cannot be perfectly tailored with a pure phase modulation [6]. However, they can be approximated by increasing the number of degrees of freedom as compared to a sinusoidal modulation. Since the spectra are composed of Dirac peaks, the phase modulations \( \phi(t) \) can be developed in Fourier series:

\[
\phi(t) = \exp \left( i \sum_{n=1}^{N} m_n \sin(2\pi f_m t + \varphi_n) \right)
\]

where \( N \) is the number of harmonics of \( f_m \), \( m_n \) the modulation depth of the \( n^{th} \) harmonic and \( \varphi_n \) its relative phase (Figure 2).

Figure 2: Non-sinusoidal modulation scheme and picture of one electrical 3-harmonic generator (\( f_m = 10 \text{GHz} \), \( N = 3 \)). The different harmonic amplitudes \( m_n \) and phases \( \varphi_n \) can be adjusted separately.
Since $\varphi_1$ can be used as phase reference ($\varphi_1=0$) without lack of generality, the number of degrees of freedom is $2N-1$. We choose $N=3$, which is a good trade-off between complexity and flatness performance (see Figure 3). Note that $N=1$ corresponds to the sinusoidal case. We have designed two prototypes of electrical drivers with $N=3$ to generate the spectra, one with $f_m=2\text{GHz}$ and the other with $f_m=10\text{GHz}$ (Figure 2).

![Figure 3: Error between the spectrum obtained with a non-sinusoidal phase modulation and the ideal spectrum versus the number of harmonics $N$ for an ideal spectrum composed of $M=25$ Dirac peaks.](image)

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To avoid shifting the laser wavelength when switching the phase modulation on and off, a symmetrical spectrum is required. This condition leads to $\varphi_2=90^\circ$ and $\varphi_1=180^\circ$ [6]. Then, optimizing $m_1$, $m_2$ and $m_3$ to obtain a flat spectrum yields almost constant values of $m_1$ and $m_3$ whatever the spectrum width. Hence, as for sinusoidal phase modulations, a single parameter ($m_2$) is sufficient to control the spectral width whatever the number of Dirac peaks $M$, as shown in Figure 4 [5].

![Figure 4: Spectra of various widths, given by the number of Dirac peaks $M$, obtained with non-sinusoidal phase modulations with $N=3$.](image)

Figure 4: Spectra of various widths, given by the number of Dirac peaks $M$, obtained with non-sinusoidal phase modulations with $N=3$. In every case, $m_1=1.4$, $\varphi_1=0$, $\varphi_2=90^\circ$, $m_2=0.4$, and $\varphi_3=180^\circ$. $m_2=2.4$ for $M=11$; $m_2=3.8$ for $M=17$; $m_2=7.1$ for $M=31$; $m_2=15.3$ for $M=65$. 

**Error function minimum**

\[
\text{Error} = \sqrt{\sum (\text{PSD}_{\text{ideal}} - \text{PSD}_{\text{modulation}})^2}
\]
3. Experiments and application to LMJ

We have used the 3-harmonic electrical drivers to generate non-sinusoidal phase modulations for the anti-Brillouin and the smoothing functions. An example of measured spectra for the anti-Brillouin function ($f_m=2\text{GHz}$) is given in Figure 5. Thanks to non-sinusoidal phase modulations, the broadening can be reduced while obtaining the same anti-Brillouin and smoothing performance. For instance, we have shown both numerically and experimentally that spectra (b) and (c) in Figure 5 have the same Brillouin threshold. Similar results were also obtained for smoothing. The broadening reduction allows an increase of the frequency conversion efficiency and a decrease of the FM-AM conversion.

Our simulations show that for LMJ an increase of 5% energy and a decrease of 1/3 of FM to AM conversion is possible thanks to non-sinusoidal modulations while keeping the same asymptotical contrast of smoothing.

References
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