Application Note 9010

Coherent Anti-Stokes Raman Scattering (CARS) - Pulse Shaping

Application Note

Revision 1.0

Boulder Nonlinear Systems, Inc.

450 Courtney Way

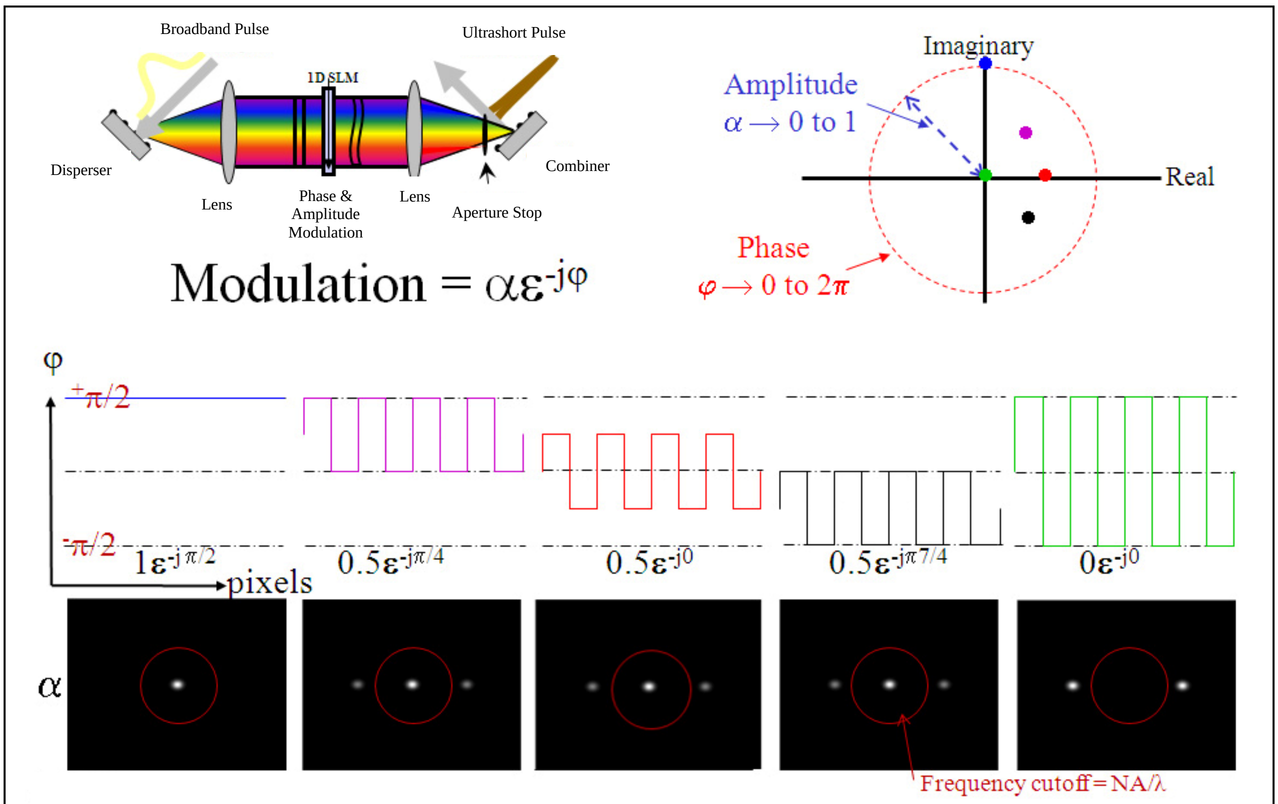
Lafayette, CO 80026-8878 USA

Coherent Anti-Stokes Raman Scattering (CARS) - Pulse Shaping

Pulse shaping benefits a variety of Coherent Anti-Stokes Raman Scattering (CARS) illumination configurations by maximizing the resonant signal and/or minimizing the non-resonant signal. In a narrowband CARS configuration, in which the frequency difference between the pump and Stokes pulse is usually scanned, pulse shaping can be used to spectrally modulate the phase of the pump and Stokes pulses [1], [2]. In a broadband CARS configuration, pulse shaping can be used to eliminate the need to overlap three independently shaped beams [3] as well as to suppress the excitation of the non-resonant vibration using coherent control methods [4], [5].

Advantages of using a BNS SLM in the design of a pulse shaper for CARS microscopy include: independent phase and amplitude modulation using only one array, high spectral resolution, improved diffraction efficiency, better waveform stability, spectral continuity and spectral range.

Independent phase and amplitude modulation:
A single BNS linear phase array can perform simultaneous independent amplitude and phase modulation. Amplitude modulation is accomplished using a phase grating within an oversampled spectral band to diffract energy out of the systems field of view [8].



Requirement: High-resolution, phase-only SLM with 3π of modulation depth

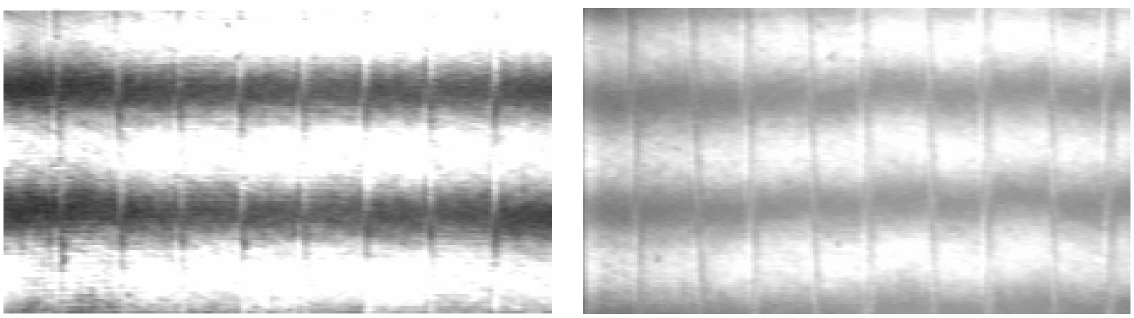
Figure 1 ~ Phase and Amplitude Modulation using diffraction.

Spectral resolution: The spectral resolution of an SLM-based pulse shaper will depend on the bandwidth of the pump pulse and the degrees of freedom offered by the SLM device.

$$\text{spectral resolution} = \frac{\text{pulse bandwidth}}{\#\ \text{of degrees of freedom}}$$

An SLM with smaller pixels and low inter-pixel cross-talk will make a pulse shaper with higher spectral resolution. Pixel cross-talk limits the frequency of phase modulation to a period smaller than actual number of pixels available.

The total number of pixels across which cross-talk will occur in a BNS linear phase array depends on a number of design parameters such as the design wavelength and the reflectivity requirement. As a result, the maximum frequency of phase modulation will vary with the SLM design.



1.064 micron device without mirror — 1.064 micron device with mirror

Figure 2 ~ Interferometer images of two 512 x 512 SLMs (left – without mirror, right - with mirror) operating at 1064 nm. The pattern written to the SLM has 15 pixels set to zero phase and 16 pixels set to 2π phase. The discontinuities in the horizontal fringe pattern show the relative width of the 2π transitions.

Transmission/ zero-order high diffraction efficiency:
A pure phase SLM with high zero-order diffraction efficiency wastes less energy and minimizes non-resonant signal strength by maximizing the percentage of modulated to un-modulated pulse energy. BNS achieves high diffraction efficiency by designing and fabricating SLMs with a 100% fill-factor.

Waveform Stability: Changing illumination pulse parameters during scanning are a source of noise. Therefore pulse stability over the length of the scan is desirable [6]. In a multiple laser system illumination scheme, the stability of the waveform also depends on the consistency of the timing between pump and Stokes pulses. Time dependent phase error, caused by LC relaxation during the electronic addressing period, is eliminated in the BNS linear SLM by addressing the pixels at kHz rates. Phase masks remain essentially static over the duration of the microscope scan.

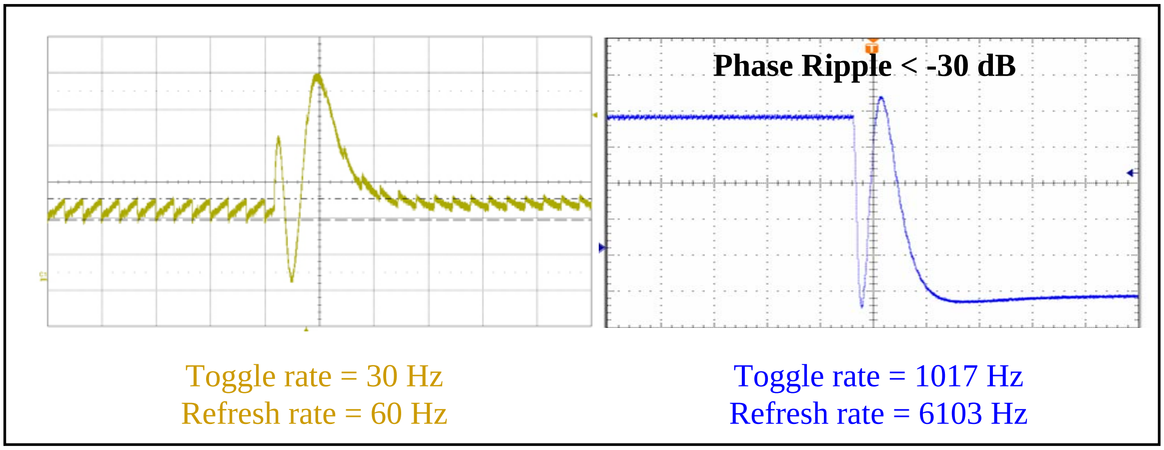


Figure 3 ~ ECB modulators addressed at different rates. The left trace shows a strong data-dependent ripple that is synchronous with the video rate addressing period. The right trace shows the ripple being suppressed by sub-millisecond refresh rates.

Spectral Continuity: Although the SLM is a pixilated device, the BNS SLMs pixels are coated with a dielectric mirror stack which allows more light to be reflected, reduces diffraction at the pixel edges, and smoothes the phase modulation between pixels so that there are no abrupt changes in phase modulation. As a result, the BNS SLM can be used as a continuously tunable spectral phase and amplitude modulator.

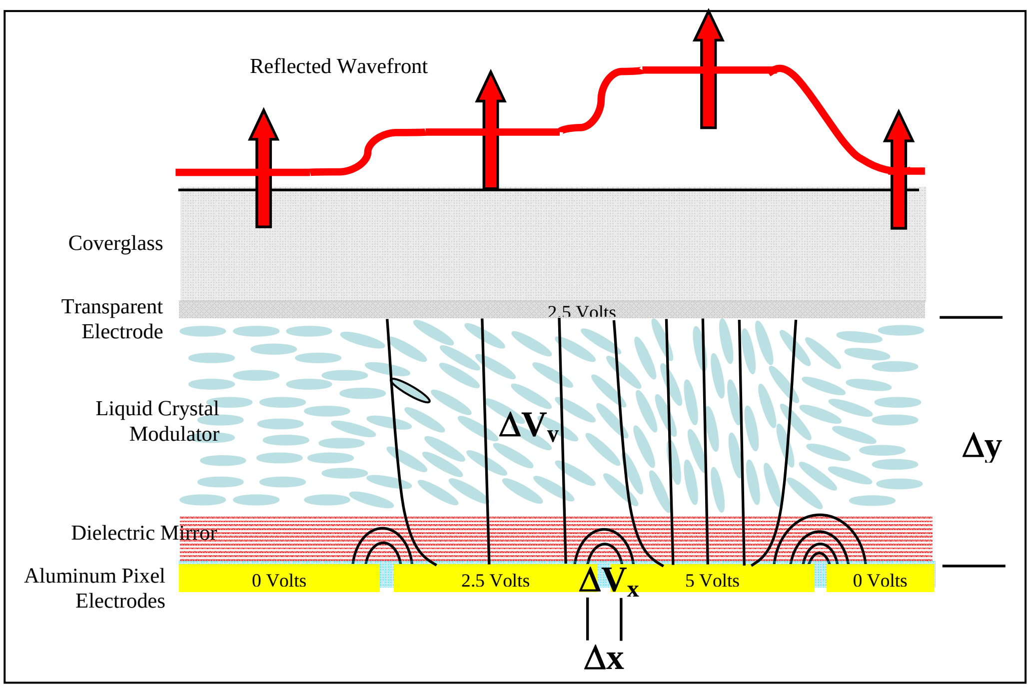


Figure 4 ~ Planarized dielectric mirror and smoothing of the electric field eliminate most of the grating effects associated with pixilated spatial light modulators.

Spectral range: There are many advantages to using a NIR source when imaging tissue such as increased depth penetration and reduced non-resonant signal strength. Evan and Xie [7] recommend a pump wavelength range of 780-980nm and a Stokes wavelength range of 1000-1300nm as optimal for biological applications.

References:

[1] Rhiannon Porter, Fang Shan, and Ting Guo, "Coherent anti-Stokes Raman scattering microscopy with spectrally tailored ultrafast pulses", *Rev. Sci. Inst.* **76**, 043108 (2005).

[2] Dmitry Pestov, Xi Wang, Robert K. Murawski, Gombojav O. Ariunbold, Vladimir A. Sautenkov, and Alexei V. Sokolov, "Pulse shaping for mode-selective ultrafast coherent Raman spectroscopy of highly scattering solids", *J. Opt. Soc. Am. B*, **25** (5), 768 (2008).

[3] N. Dudovich, D. Oron, and Y. Silberberg, "Single-pulse coherently controlled nonlinear Raman spectroscopy and microscopy," *Nature* **418**, 512-514 (2002).

[4] D. Oron, N. Dudovich, and Y. Silberberg, "Single-pulse phase-contrast nonlinear Raman spectroscopy," *Phys. Rev. Lett.* **89**, 273001 (2002).

[5] S. Postma, A. C. W. van Rhijn, J. P. Korterik, P. Gross, J. L. Herek, and H. L. Offerhaus, "Application of spectral phase shaping to high resolution CARS spectroscopy," *Opt. Express* **16**, 7985-7996 (2008)

[6] A. Volkmer, "Topical Review: Vibrational imaging and microspectroscopies based on coherent anti-Stokes Raman scattering microscopy", *J. Phys. D: Appl. Phys.*, **38**, R59–R81 (2005).

[7] C. L. Evans and X. S. Xie, "Coherent Anti-Stokes Raman Scattering Microscopy: Chemical imaging for Biology and Medicine", *Annu. Rev. Anal. Chem.*, 8333-909 (2008).

[8] Jesse W. Wilson, Philip Schlup, and Randy A. Bartels, "Ultrafast phase and amplitude pulse shaping with a single, one-dimensional, high-resolution phase mask", *Opt. Express*, 15 (14), 8980 (2007).

Company Profile

Boulder Nonlinear Systems, Inc. (BNS) is an innovative technology company specializing in dynamic liquid crystal polarization control solutions for both laser-based and imaging systems. Company strengths in scientific research and development are leveraged into OEM and standard product offerings targeted for astronomy, biomedical, defense, microscopy, optical computing, optical storage, and telecommunications applications.

For additional product and company information, please contact:

Boulder Nonlinear Systems, Inc.
450 Courtney Way
Lafayette, CO 80026 – 8878
USA
Website: www.bnonlinear.com

Telephone: (303) 604 – 0077
Toll free: (866) 466 – 0506
Fax: (303) 604 – 0066
E-mail: sales@bnonlinear.com