

# Optimal pulse width modulation for sinusoidal fringe generation with projector defocusing: reply to comment

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We found that there were some inaccurate comments in the Comment by Ayubi and Ferrari [Opt. Lett. **36**, xxxx (2011)] on our optimal pulse width modulation Letter [Opt. Lett. **35**, 4121 (2010)]. This Letter is to clarify some of the technical misunderstandings. © 2011 Optical Society of America

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In the Comment by Ayubi and Ferrari [1] on the optimal pulse width modulation (OPWM) Letter [2], we found some inaccurate comments that might result from their misunderstandings. This Letter is to clarify some misunderstandings from technical aspects.

*Clarification 1: criteria on squared binary method (SBM) and sinusoidal pulse-width-modulation method (SPWM) comparison.* To overcome some of the limitations of the SBM [3], Ayubi and Ferrari and co-workers proposed an interesting SPWM technique [4], which focuses on shifting high-order harmonics so that they could be more easily suppressed by defocusing. We completely agree that, in a continuous space, the SPWM should always be better than the SBM. However, in a discrete space, because of sampling, the SPWM has limitations. To maintain the fundamental difference between the SPWM and the SBM, our comparison was based on the assumption that the modulation frequency  $f_c$  is much higher than the base frequency  $f_0$ , i.e.,  $f_c \gg f_0$ . We mentioned that the  $f_c$  was optimized, but did not thoroughly address the optimization criteria. In brief, we chose the modulation period  $T_c = 1/f_c = 2n < 1/f_0$  ( $n$  is an integer), and selected the optimal frequency  $f_c = 1/T_c$  to minimize the phase error. We are currently working on a full-length paper to thoroughly compare the SBM, the SPWM, and the OPWM [5].

*Clarification 2: description of OPWM.* We understood that  $a_0 = 0$  is not the case for a real fringe pattern. However, as explained in our Letter, to simplify mathematical descriptions, we illustrated our signal to be symmetric to the  $x$  axis with mean being zero. We do not think this will prevent the understanding of the OPWM concepts because we often refer to a sinusoidal fringe pattern without mentioning its mean. Because of the page limit, we did not include sufficient details on notch setting, which will also be thoroughly covered in our working paper [5].

*Clarification 3: emulation of sinusoidal patterns.* It is absolutely correct to comment that our OPWM Letter [2] did not strive to emulate better appearing sinusoidal patterns! Instead, we focus on improving the three-dimensional (3D) shape measurement quality. In other words, our ultimate goal is to obtain better phase instead of better sinusoidal patterns. In fact, our research has

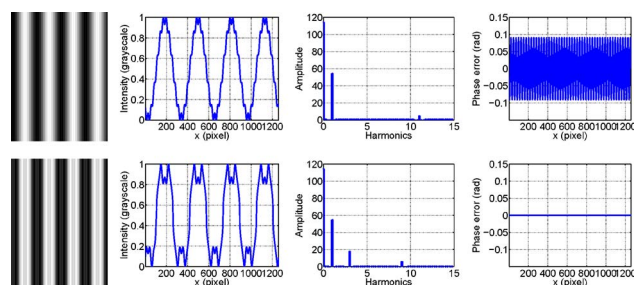


Fig. 1. (Color online) Influence of high-order harmonics on phase error. First row shows 1 + 11-order and second row shows 1 + 3 + 9-order harmonics. Left to right columns: one of three fringe patterns with equal phase shift, cross sections, frequency spectra, and resultant phase errors.

found that: (a) it is not sufficient to look at the appearance of fringe patterns, nor their frequency spectra; (b) for a three-step algorithm with equal phase shift, the  $3n$ th-order ( $n$  is an integer) harmonics do not induce any phase error; (c) even if the fringe patterns appear to be binary, they could still be used to perform high-quality 3D shape measurement if a proper phase-shifting technique is utilized. The example in Fig. 1 clearly shows that the lower quality sinusoidal patterns could have smaller phase errors (thus better measurement quality) than those seemingly better sinusoidal ones.

In summary, the inaccurate comments of the Comment by Ayubi and Ferrari might mostly come from the misunderstanding of the ultimate goal of our OPWM technique: obtaining better phase for better quality 3D measurement. We hope that this Letter has elucidated the major concerns from technical aspects.

## References

1. G. A. Ayubi and J. A. Ferrari, Opt. Lett. **36**, xxxx (2011).
2. Y. Wang and S. Zhang, Opt. Lett. **35**, 4121 (2010).
3. S. Lei and S. Zhang, Opt. Lett. **34**, 3080 (2009).
4. G. A. Ayubi, J. A. Ayubi, J. M. D. Martino, and J. A. Ferrari, Opt. Lett. **35**, 3682 (2010).
5. Y. Wang and S. Zhang are preparing a manuscript to be called "Comparison between SBM, PWM, and OPWM for 3D shape measurement."