Fabrication and testing of binary-phase Fourier gratings for nonuniform array generation

Andrew S. Keys
NASA Marshall Space Flight Center, National Space Science and Technology Center, 320 Sparkman Drive, Huntsville, AL 35805
andrew.keys@nasa.gov

Robert W. Crow
Sensing Strategies, Inc., 114 Titus Mill Road, Pennington, NJ 08534
rcrow@sensingstrategies.com

Paul R. Ashley
US Army Aviation and Missile Command, Redstone Arsenal, AL 35898
paul.ashley@us.army.mil

Tom R. Nelson, Jr.
Air Force Research Laboratory, SNDD, 2241 Avionics Circle, Wright-Patterson AFB, OH 45433-7322
thomas.nelson@wpafb.af.mil

Jack H. Parker
Air Force Research Laboratory, SNJT, 2241 Avionics Circle, Wright-Patterson AFB, OH 45433-7322
jack.parker@wpafb.af.mil

Elizabeth A. Beecher
Air Force Research Laboratory, SNJT, 2241 Avionics Circle, Wright-Patterson AFB, OH 45433-7322
elizabeth.beecher@wpafb.af.mil

Abstract: This effort describes the fabrication and testing of binary-phase Fourier gratings designed to generate an incoherent array of output source points with nonuniform user-defined intensities, symmetric about the zeroth order. Like Dammann fanout gratings, these binary-phase Fourier gratings employ only two phase levels to generate a defined output array. Unlike Dammann fanout gratings, these gratings generate an array of nonuniform, user-defined intensities when projected into the far-field regime. The paper describes the process of design, fabrication, and testing for two different version of the binary-phase grating; one designed for a 12 μm wavelength, referred to as the Long-Wavelength Infrared (LWIR) grating, and one designed for a 5 μm wavelength, referred to as the Mid-Wavelength Infrared Grating (MWIR).

OCIS codes: (050.1380) Binary optics; (070.2580) Fourier optics.

1. Introduction to binary-phase Fourier gratings

Phase-only Fourier gratings [1] provide a method for transforming a single input beam into a custom array of one- or two-dimensional source points or images. As a subset of phase-only gratings, binary-phase gratings employ discrete phase levels to produce the desired far-field diffractive source point array pattern. If the binary-phase grating design is limited to only two phase levels, say 0 and π, ease of grating fabrication is increased while output efficiency is decreased. To counter the loss in output efficiency attributable to a reduced number of phase levels available for grating design, phase transition locations within the grating period may be considered as design variables. Dammann [2,3] is widely credited as providing the initial development and analytical treatment of this approach to fanout grating design by treating the positions of the phase transition between two binary phase levels as the design variables. A mathematical Fourier transform of the phase transition locations provides a solution to the far-field source point array, hence the name Fourier grating.

This effort to develop binary-phase Fourier gratings differs from others in that the specifications for the grating output require a symmetric, but nonuniform intensity distribution within the transmitted grating orders. The grating design for this unique requirement involves a search of the variable space using optimization algorithms to locate the optimal design parameter values. While the design process has been described elsewhere [4], this current effort describes the process of fabricating and testing the results of the design effort.

2. Fabrication of binary-phase Fourier gratings

The gratings produced as a result of this effort exhibit a user-defined symmetric, nonuniform, incoherent source array as the grating response to a single input beam. The desired normalized intensity distribution is listed per transmitted order in Table 1a. Per the results of the optimized variable space search, the locations of the phase transitions that provided the design of highest efficiency and closest match to the desired normalized intensity distribution are listed in Table 1b. This design is presented graphically in Figure 2 as a representation of the grating's surface profile. The efficiency of this design is calculated to be 72.1228%.

Table 1a: Normalized Design Intensities per Diffractive Order

Order No.	Relative Target Intensities
-4	0.0500
-3	0.1000
-2	0.3000
-1	0.6000
0	1.0000
1	0.6000
2	0.3000
3	0.1000
4	0.0500

Table 1b: Phase Transition Locations for Remote Sensor Grating

Transition No.	Phase Transition Location
z_{-3}	-0.0034
z_{-2}	0.0875
z_{-1}	0.1120
z_1	0.2512
z_2	0.4729
z_3	0.5000

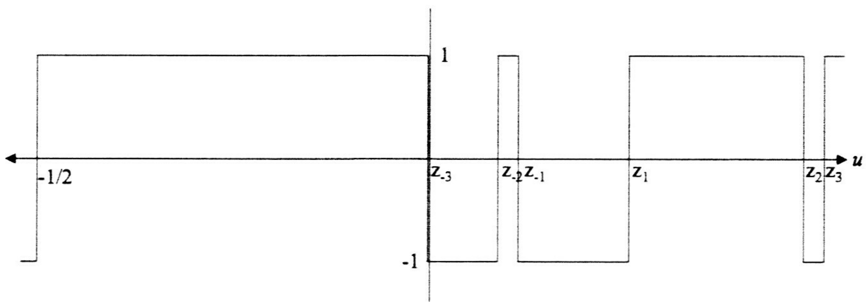

Fig. 1. Optimized remote sensor grating design showing relative phase transition locations within a single period.

The gratings' diffraction angles are calculated from the grating equation for normal incidence

$$a \sin\theta_m = m\lambda \tag{1}$$

where a is the grating period length, λ is the grating's design wavelength, m is the diffraction order, and θ_m is the angle of diffraction for the m order. The grating designed for a 12 μm source wavelength is fabricated with a grating period of 120 μm, providing a first order angle of propagation equal to 5.74 degrees and the angle of fourth order propagation is 23.58 degrees. Likewise, the grating designed for a 5 μm source wavelength is fabricated with a grating period of 50 μm, allowing all transmitted orders to have the same propagation angles as those of the 12 μm grating.

The grating etch depth, d, is determined by the equation

$$d = \frac{\lambda}{2(n_\lambda - 1)} \tag{2}$$

where n_λ is the refractive index of the material at the grating's design wavelength. Per reference [5], GaAs, the selected grating substrate material, has a refractive index of n = 3.2671 at 11.27 μm and n = 3.2597 at 12.40 μm. Linear interpolation for 12.00 μm gives n = 3.2623, resulting in a etch depth of 2.65 μm. Likewise, GaAs has a refractive index of n = 3.2978 at 4.959 μm and n = 3.2968 at 5.166 μm. Linear interpolation for 5.00 μm gives n = 3.2976, resulting in a etch depth of 1.09 μm.

The grating design represented in Table 1a is not dependent on wavelength, hence it applies to both the LWIR and MWIR designs. Chrome photomasks for both designs were fabricated. Blank GaAs wafers were spin-coated with Shipley 1818 photoresist and exposed using the chrome photomask. The etching of the gratings was done using a reactive ion etcher and a chlorine-based gas chemistry. The gratings were then diced into their final sizes using a nickel-bladed dicing saw.

3. Testing of binary phase Fourier gratings

Experimental testing of both the LWIR and MWIR grating designs emphasized the gratings' ability to exhibit intensities that are of the appropriate magnitude when compared to the zeroth transmitted order. The test set-up is shown schematically in Figure 2. A CO2 laser was used to get preliminary results from the LWIR, even though the output wavelength from a CO2 laser at 10.6 μm is somewhat shorter than the design wavelength of 12 μm. For the MWIR, a blackbody radiator is used as the source. It is projected through both a slit to spatially collimate the source and a bandpass filter centered on 5 μm to isolate a narrow frequency band. The results of the measured data verses the specified intensity amplitudes are shown below in Figure 3.

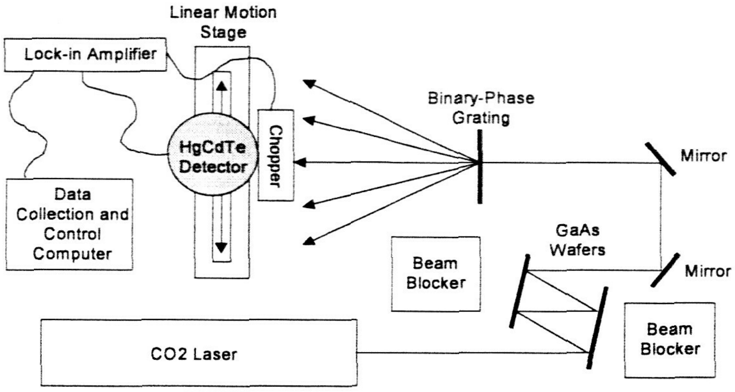

Fig. 2. Schematic of Laboratory Set-up Used to Characterize 12 um Binary-Phase Grating

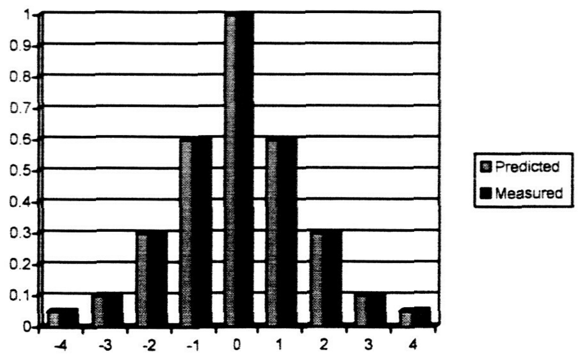

Fig 3. Plot of Normalized Design Magnitudes versus Actual Measured Data

4. References

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