Blazed grating-coupled AR waveguides made by contact-mode lithography at Inprentus

Nick Toombs, Samuel Gleason, Xuefei Guo, Cody Jensen, Subha Kumar, Peter Abbamonte
Inprentus, Inc., 51 E. Kenyon Rd., Champaign, IL, 61820, USA

INTRODUCTION

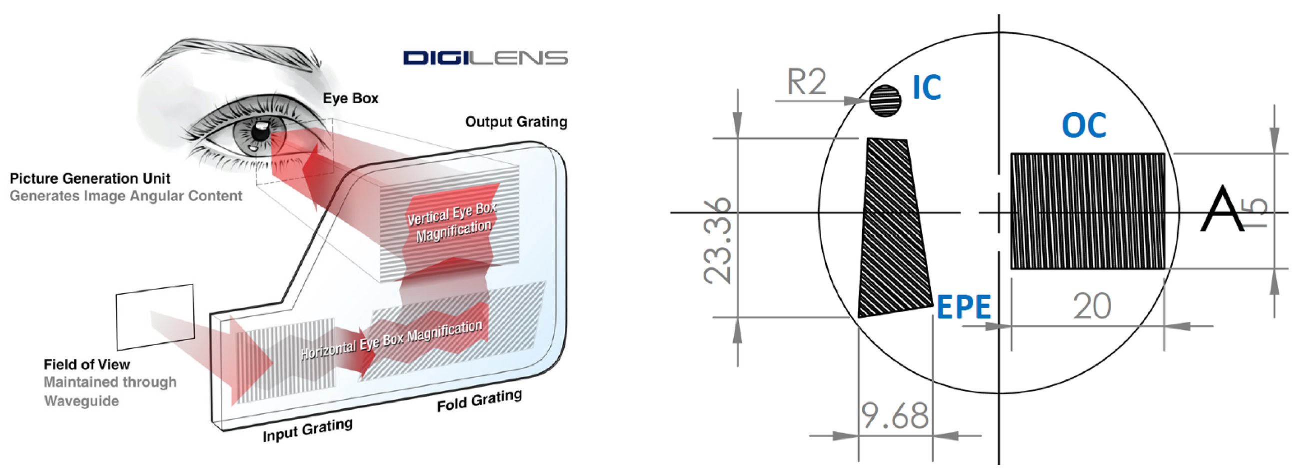

Figure 1. AR eyepieces, made of grating-coupled waveguides, act as a beam expanding periscope [1]

Desirable grating properties:

- Controllable efficiency (high or low)
- High directionality
- Pitch uniformity Δd<100 pm
- Modulation
- Simple manufacturing
- Easy to replicate

CONTACT MODE LITHOGRAPHY SIMPLIFIES MASTERING

Figure 2. Inprentus manufacturing facility featuring three ruling engines in an environment-controlled cleanroom.

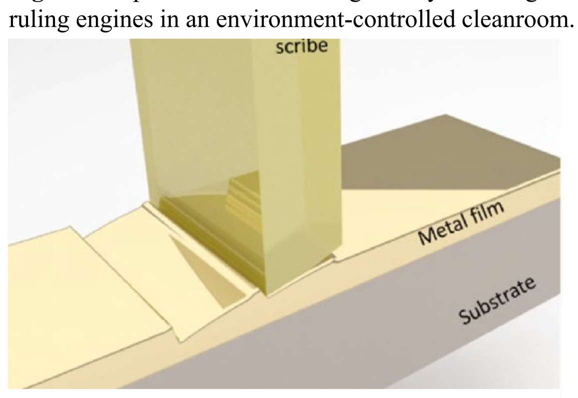

Figure 3. Cross-section schematic of diamond scribe burnishing process for fabrication of blazed gratings.

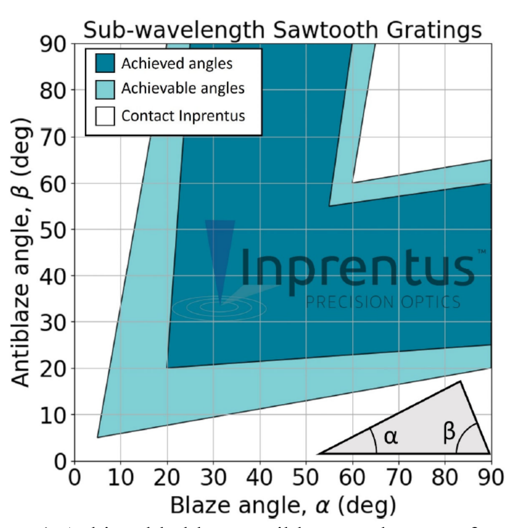

Figure 4. Achievable blaze-antiblaze angle space for mechanical ruling process.

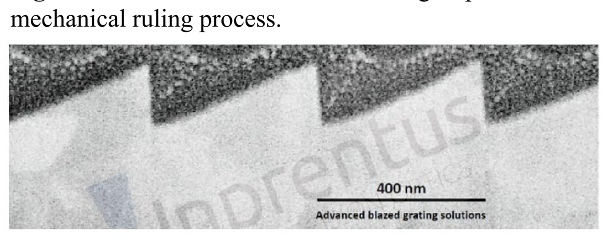

Figure 5. Cross-section SEM of typical Inprentus AR grooves. Blaze = 44° ; Antiblaze = 79°

- Novel contact mode lithography technique (mechanical ruling) is a simple one-step process for making blazed master gratings
- No post-processing required!
- Fabricated in Inprentus clean-room facility located in Champaign, IL
- Grooves are serially inscribed into a metal (typically Au) film using a diamond tool
- Groove positions are controlled using laser interferometers
- Pitch and blaze can be modulated across the surface
- In situ AFM monitors groove profile
- Groove density 50- 6000 lines per millimeter
- Wide selection of groove angles available
- Detailed structural and optical characterization of gratings available

INPRENTUS BLAZED GRATING ADVANTAGES

TUNABILITY

- High or low efficiency
- Tunable response curve

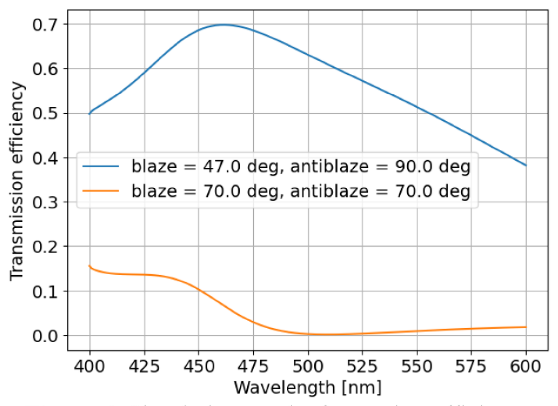

Figure 6. Simulation results for grating efficiency as a function of wavelength for two different blazed groove profiles.

DIRECTIONALITY

- Asymmetric groove property
- Low eye-glow

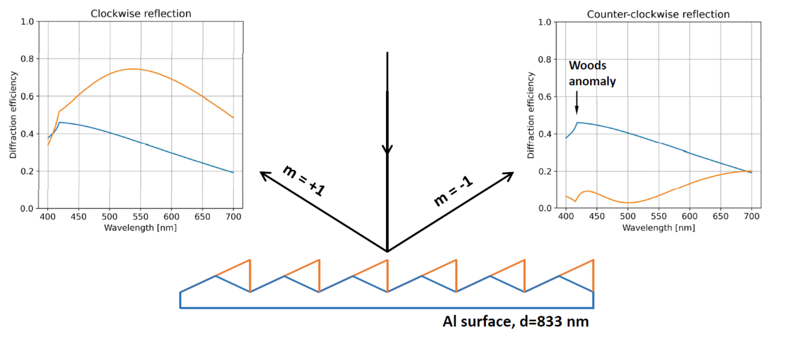

Figure 7. Simulation results for symmetric (blue) and asymmetric or blazed (orange) groove profile. The blazed groove shape allows for high efficiency in the +1 order and low efficiency in the -1 order.

REPLICATION FRIENDLY

- Replicas separate easily
- NIL compatible

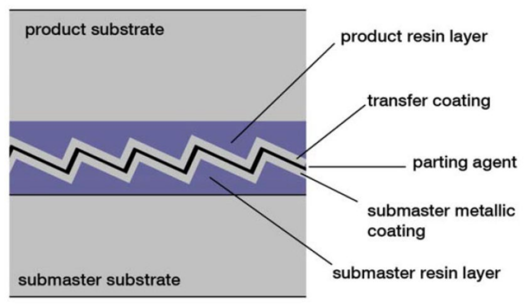

Figure 8. Nano-imprint Lithography (NIL) replication of blazed grating profile.

SIMPLICITY

- One method to rule all (gratings)
- Easy to realize design efficiencies

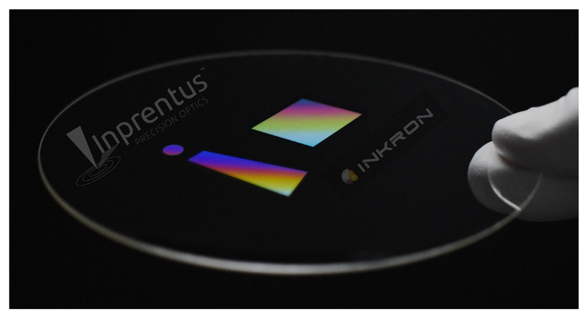

Figure 9. Three-grating AR waveguide in 1.9 index resin. Master fabrication by Inprentus and NIL replication by Inkron.

FLEXIBILITY

- Modulated grooves (3-5 x efficiency enhancement with blazed design kit)
- Curved lines

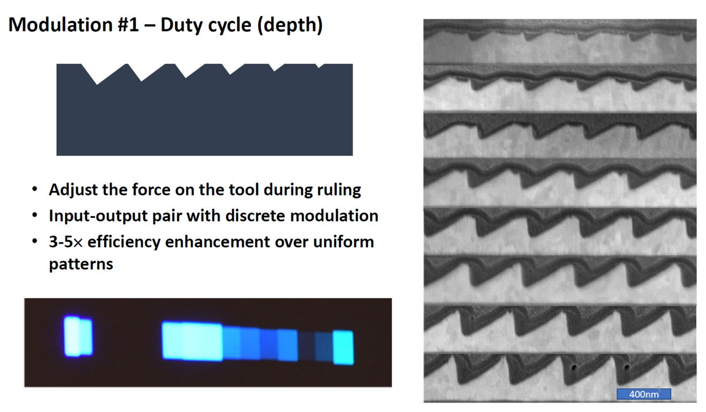

Figure 10. Cross-section SEM micrograph of grating pattern with groove depth modulation. Top-down color image of modulated grooves with varied efficiencies.

PITCH UNIFORMITY

- No minimum write fields
- < 20 pm measured with Fizeau interferometer [2]

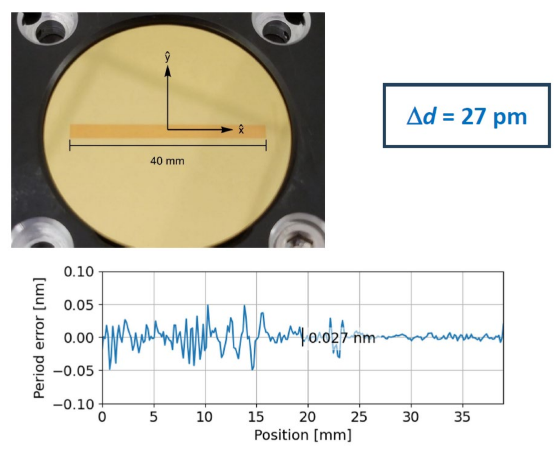

Figure 11. Line spacing (period) error as a function of grating position for a 40 mm long grating pattern.

LOW STRAY LIGHT ("HAZE")

- < 0.2%
- Low line positioning error

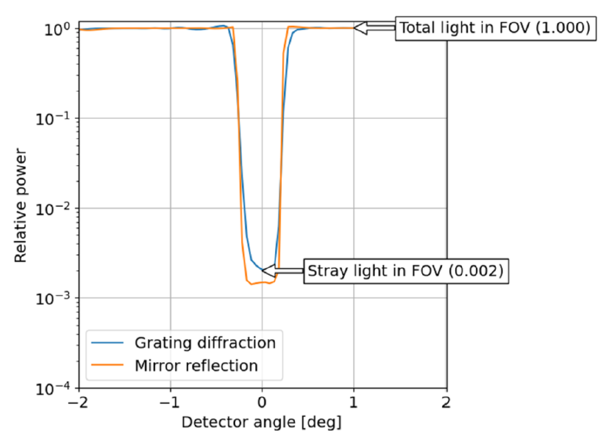

Figure 12. Stray light measurement for an AR grating master. Best case mirror reflection (orange) and grating diffraction blue)

CROSSED GRATINGS

- Rule lines, rotate, rule lines
- 2D array of pillars with angled facets

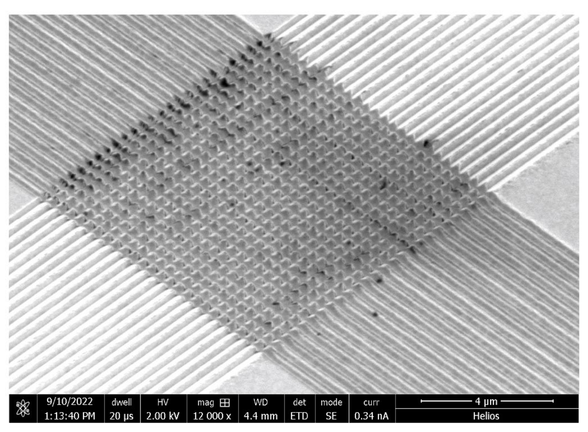

Figure 13. crossed grating pattern showing AR-type grooves ruled with perpendicular trajectories.

Key Specs:

- **Ruling layer:** Au plus coatings (Al, Ni, C, etc.)
- **Blaze angle accuracy:** ±0.1°
- **Blaze angle range:** 20°-80° (0.1°-80°)
- **Orientational accuracy:** 10 µrad (2 µrad)
- **Pitch accuracy:** 20 pm (demonstrated)
- **Modulated and aperiodic patterns**

Key Differentiators:

- **Simplicity** – Same method for whole eyepiece
- **Replication** – compatible with NIL
- **Tunable** – Efficiency, response curves
- **Directional** – Important for IC
- **Modulation** – aperiodic/curved grooves
- **Coherence** – No write field stitching

DESIGN & MEASUREMENT OF BLAZED I/P-O/P COUPLERS

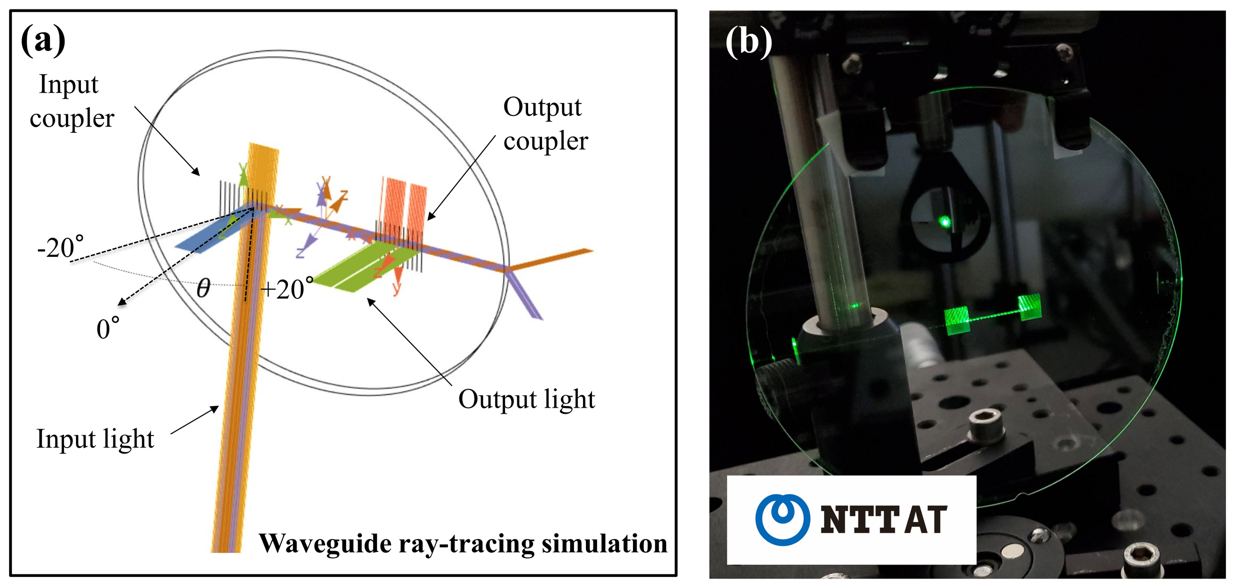

Figure 14. (a) Ray-tracing simulation for a two-grating waveguide device showing the trapped and un-trapped light rays. (b) Two-grating prototype setup for efficiency measurements on a diffractometer.

- Full waveguide simulations with ray-tracing and RCWA of blazed gratings, shown in Fig. 14a, provide target design blaze angles for manufacturing and simulate the optical response of manufactured grooves from the final input-output coupler device (Fig. 14b).

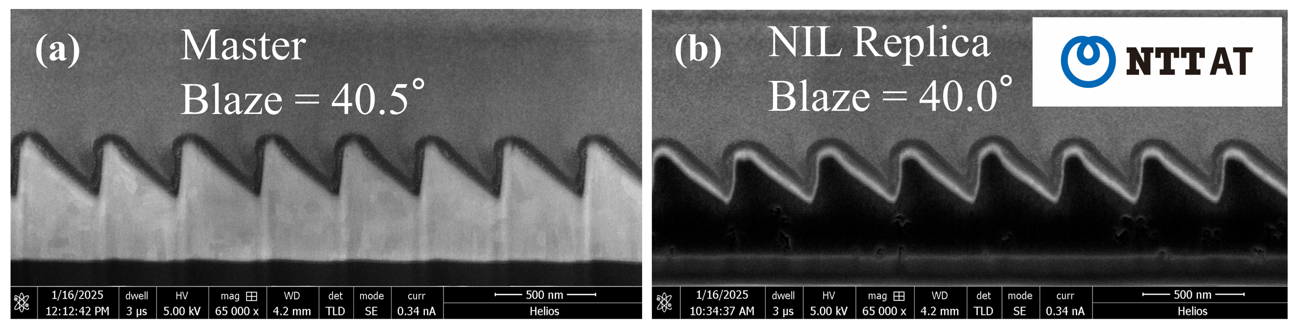

Figure 15. SEM micrographs of (a) master grating groove profile ruled in gold and (b) replicated grating groove profile.

- Master device ruled by Inprentus and NIL imprints made in high refractive index resins (n=1.9) show angles are well preserved.

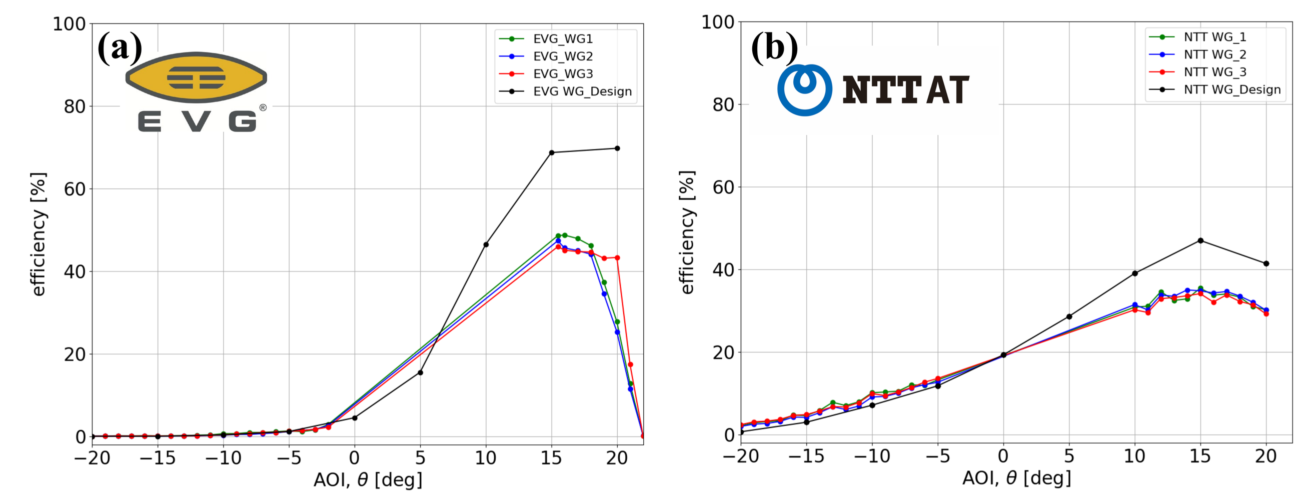

Figure 16. Designed and measured efficiency response curves for waveguides with identical input and output coupler gratings. Both couplers have a 400 nm pitch. The blaze and antiblaze angles and index of refraction are (a) 60.5°,87.9°, n = 1.7 and (b) 40.0°,85.0°, n = 1.9 respectively.

- Optical efficiency of waveguide replicas are measured on an in-house diffractometer using a monochromatic source
- AR waveguides with blazed couplers achieve peak efficiencies of up to 48%

CONCLUSIONS

- Inprentus has achieved design control of efficiency over FOV.
- Blazed waveguide couplers manufactured from masters made using Inprentus contact mode lithography deliver designed response curves with high peak efficiencies.

REFERENCES

1. B. C. Kress, I. Chatterjee, *Nanophotonics*, **10**, 41-74 (2021)
2. S. Gleason, et al. Proc. SPIE **10105**, UNSP 1038506 (2017)