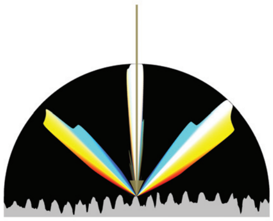


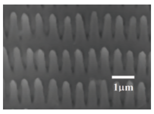
INTERACTIVE DIFFRACTION FROM BIOLOGICAL NANOSTRUCTURES

Daljit Singh J. S. Dhillon[1] Jeremie Teyssier[2] Michael Single[1] Iaroslav Gaponenko[2]
Michel C. Milinkovitch[3] and Matthias Zwicker[1]

[1] Computer Graphics Group, Institute of Computer Science and Applied Mathematics, University of Bern, Bern, Switzerland.
[2] DMPC, University of Geneva, Geneva 4, Switzerland.
[3] Laboratory of Artificial and Natural Evolution (LANE), Department of Genetics and Evolution, University of Geneva, Geneva, Switzerland.

PROBLEM

(a) Xenopeltis



(b) Its nanostructure

Goals :

1. Rendering structural colors due to diffraction,
2. For biological nanostructures,
3. At interactive rates.

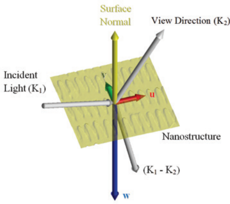
Challenges :

- Natural complexity of biological nanostructures.
- Performing complex computations in real-time at high resolution.

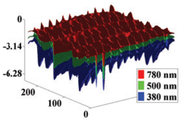
Our Contributions :

- A method to render structural colors due to *generic diffraction gratings* directly based on physical measurements with atomic force microscopy (No assumptions about the *bump* distribution).
- An algorithm for interactive rendering leveraging precomputed look-up tables.

METHOD



(a) Optical Geometry



$$\Phi(x,y) = \tfrac{2\pi}{\lambda} w h(x,y)$$
$$p(x,y) = e^{i\Phi(x,y)}$$

(b) Phase shifts $\Phi(x,y)$ for different wavelengths

Bidirectional reflection distribution function is given as [1]:

$$BRDF_{\lambda}(\omega_i,\omega_r) = \frac{F^2 G}{\lambda^2 A w^2}\left\langle \left| P\left(\frac{u}{\lambda},\frac{v}{\lambda}\right)\right|^2 \right\rangle .$$

Spectral integration gives luminance as :

$$Y \propto \int_{\lambda} BRDF_{\lambda}(\omega_i,\omega_r) S_y(\lambda) \mathrm{d}\lambda .$$

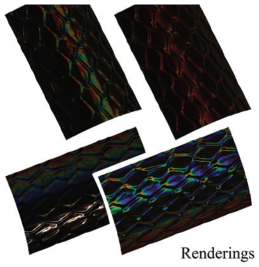
We propose the following adaptation + optimization:

$$\mathbf{P}\left(\frac{\mathbf{u}}{\lambda},\frac{\mathbf{v}}{\lambda}\right) \propto \sum_{\mathbf{n}=0}^{\infty} \frac{(\mathbf{wk})^{\mathbf{n}}}{\mathbf{n}!}\left[\mathbf{DFT}\left\{\mathbf{i}^{\mathbf{n}}\ \mathbf{h}^{\mathbf{n}}\right\} * \mathbf{G}\right]\left(\frac{\mathbf{u}}{\lambda},\frac{\mathbf{v}}{\lambda}\right).$$

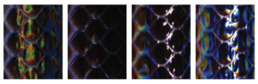
Key Ideas:

- Exploit properties of Fourier transforms to use *Discrete* Fourier transforms.
- Use spatial coherence length to compute response for non-discrete frequencies.
- Factor out optical geometry from **DFT** operands.
- Precompute integration over wave spectrum for discretized optical geometry space $(u-v)$.
- Use relative reflectance for tone-mapping.

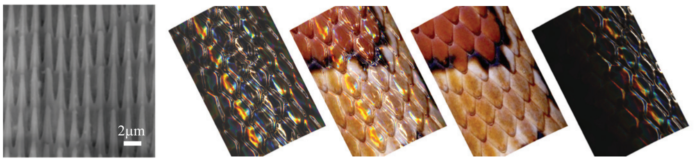
RESULTS



Renderings

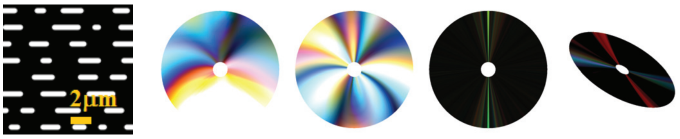


Real photographs of a *Xenopeltis*



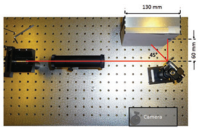
Elaphe nanostructure Diffraction Diffuse texture Diffraction + diffuse Different illumination

Elaphe Guttata Guttata

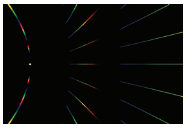


Synthetic Compact Disk (its nanostructure and different renderings)

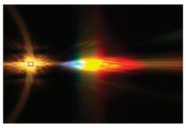
EXPERIMENTAL VERIFICATION



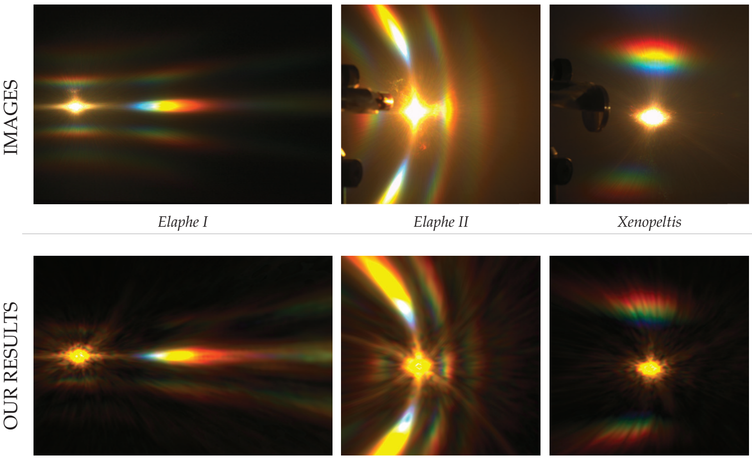
Lab setup



STAM I : *Elaphe I*



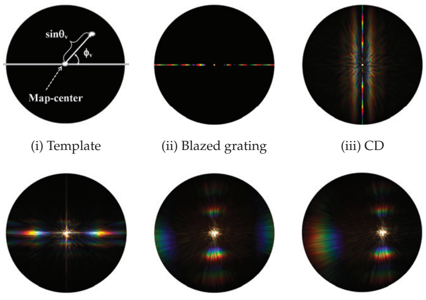
STAM II : *Elaphe I*



Elaphe I *Elaphe II* *Xenopeltis*

Elaphe I *Elaphe II* *Xenopeltis*

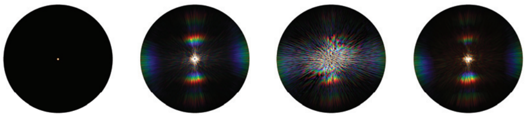
BRDF MAPS



(i) Template (ii) Blazed grating (iii) CD

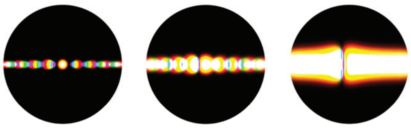
(iv) *Elaphe* (v) *Xenopeltis* (vi) *Xenopeltis*

(a) (i)-(v) Shows BRDF maps generated using normal incident light for different viewing directions (θ_r,ϕ_r). (vi) Shows BRDF map for *Xenopeltis* with incident light at an angle of 20°



(i) $N=0$ (ii) $N=1$ (iii) $N=3$ (v) $N=33$

(b) Convergence of the Taylor series with a large N for a *Xenopeltis* sample.



$4\sigma_s = 13\mu m$ $4\sigma_s = 6.5\mu m$ $4\sigma_s = 3.25\mu m$

(c) Effects of coherence length (blazed grating)

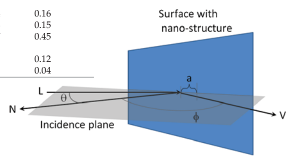
VALIDATION

We validate our method in comparison with an idealized diffraction grating defined by,

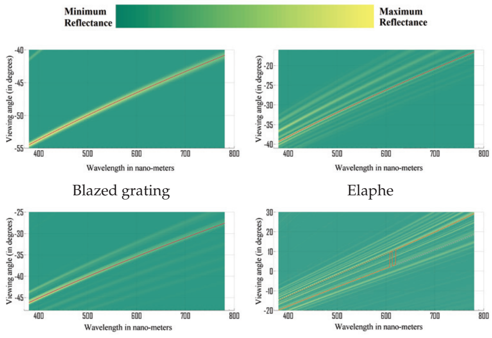
$$sin(\theta) = sin(\phi) + m\lambda/a, \tag{1}$$

where θ is the angle of incidence, ϕ is the viewing angle, m is the diffraction order, λ is a wave frequency and a is the idealized periodicity of a grating.

Nanostructure	Estimated Periodicity	
	Mean (in nm)	**Variance (in nm)**
Blazed grating (2500nm)	2500.34	0.16
Elaphe	1144.28	0.15
Xenopeltis (Along fingers)	1552.27	0.45
Xenopeltis (Across fingers)		
- Blue curve in Figure (c)	605.89	0.12
- Brown curve in Figure (c)	536.13	0.04



(a) Experimental Setup



Blazed grating Elaphe

Xeno : Along nano-fingers Xeno : Across nano-fingers

(b) Relative spectral reflectance for incidence angle fixed at 75°

CONCLUSION

Our approach achieves interactive performance (upto 120 FPS) by precomputing spectral integrals into look-up tables using a Taylor series expansion. Future work would extend our method for modeling diffraction from other biological nanostructures such as multilayer arrangement on butterfly wings.

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REFERENCES

[1] STAM J.: "Diffraction Shaders", In *Proceedings of the 26th annual conference on computer graphics and interactive techniques, SIGGRAPH '99.*

[2] CUYPERS T., HABER T., BEKAERT P., OH S. B., RASKAR R.: "Reflectance model for diffraction", In *ACM Trans. Graph. 31, 5 (Sept. 2012).*

[3] ZIEGLER R., CROCI S., GROSS M.: "Lighting and occlusion in a wave-based framework.", In *Computer Graphics Forum 27, 2 (2008).*