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Multi-layer anti-reflection coats using ePTFE membrane for mm-wavelength plastic optics

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Designing AR Coats

Anti-reflection (AR) coats on optics are a critical component of a system, reducing light lost to reflections and preventing spurious signal from reaching detectors. Layered AR coats typically use quarter wavelength optical path lengths to produce destructive interference. Millimeter wavelength AR coats therefore exist in a unique macroscopic-but-still-thin regime; quarter wavelength optical path lengths range from 0.3 mm to 3 mm from 300 to 30 GHz.

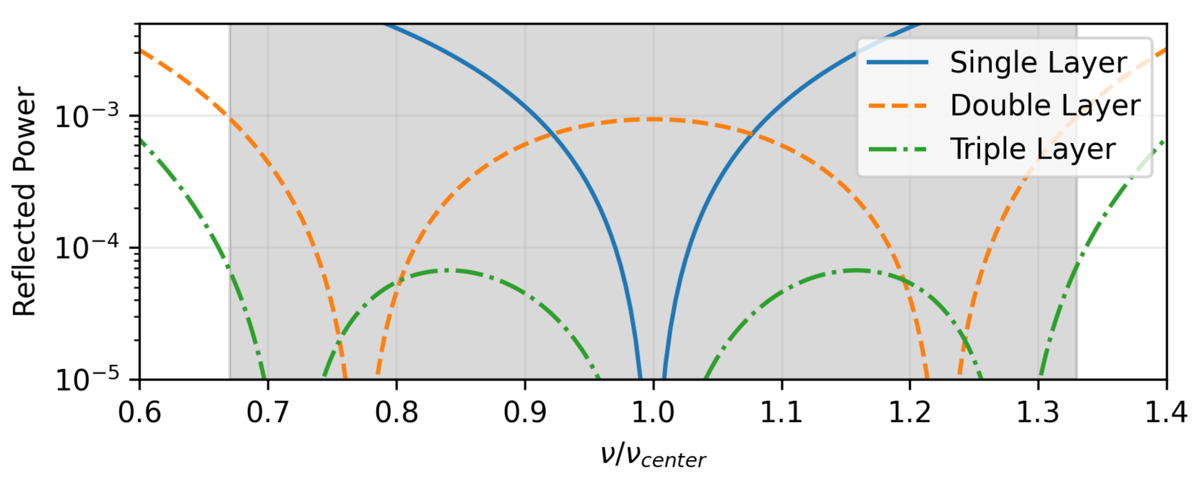

Fig. 1: Reflections from ideal single, double and triple layer anti-reflection coats for HDPE (n=1.55) over a fractional bandwidth of 0.66 (like wSMA) [6].

The lowest average in-band reflection possible with finite layers can be found with Chebyshev polynomials [1]. The quarter wavelength AR layers have equal height ripples, which minimize the reflected power within a bandwidth.

Example Double Layer Chebyshev AR Coat

$$2\Gamma_0 \cos 2\theta + \Gamma_1 = \underbrace{A \sec^2 \theta_m + A \sec^2 \theta_m \cos 2\theta - A}_{\text{Chebyshev polynomial}}$$

$$\Gamma_1 = A \sec^2 \theta_m - A$$

$$\boldsymbol{n_1 = Z_0 \exp\left[-\ln\left(\frac{Z_0}{n_2}\right) + 2\Gamma_1\right]}$$

$$2\Gamma_0 = A \sec^2 \theta_m$$

$$\boldsymbol{n_2 = Z_0 \exp\left[-\ln\left(\frac{Z_0}{n_c}\right) + 2\Gamma_0\right]}$$

A = max allowed reflection mag.
$\sec \theta_m = \cosh\left(\left|\frac{1}{N \cosh\left(\frac{n_c}{2A}\right)}\right|\right)$ = bandw.
N = number of layers
n_c = index of core
Z_0 = vacuum impedance

Practically, it is difficult to find materials that have precisely the properties required by the Chebyshev polynomials. We can design with actual materials by probing the parameter space and exploring the parameter surface that produces the minimum reflection.

Multi-layer AR Coat on Bulk HDPE (n=1.55) for BA4 (220/270 GHz)

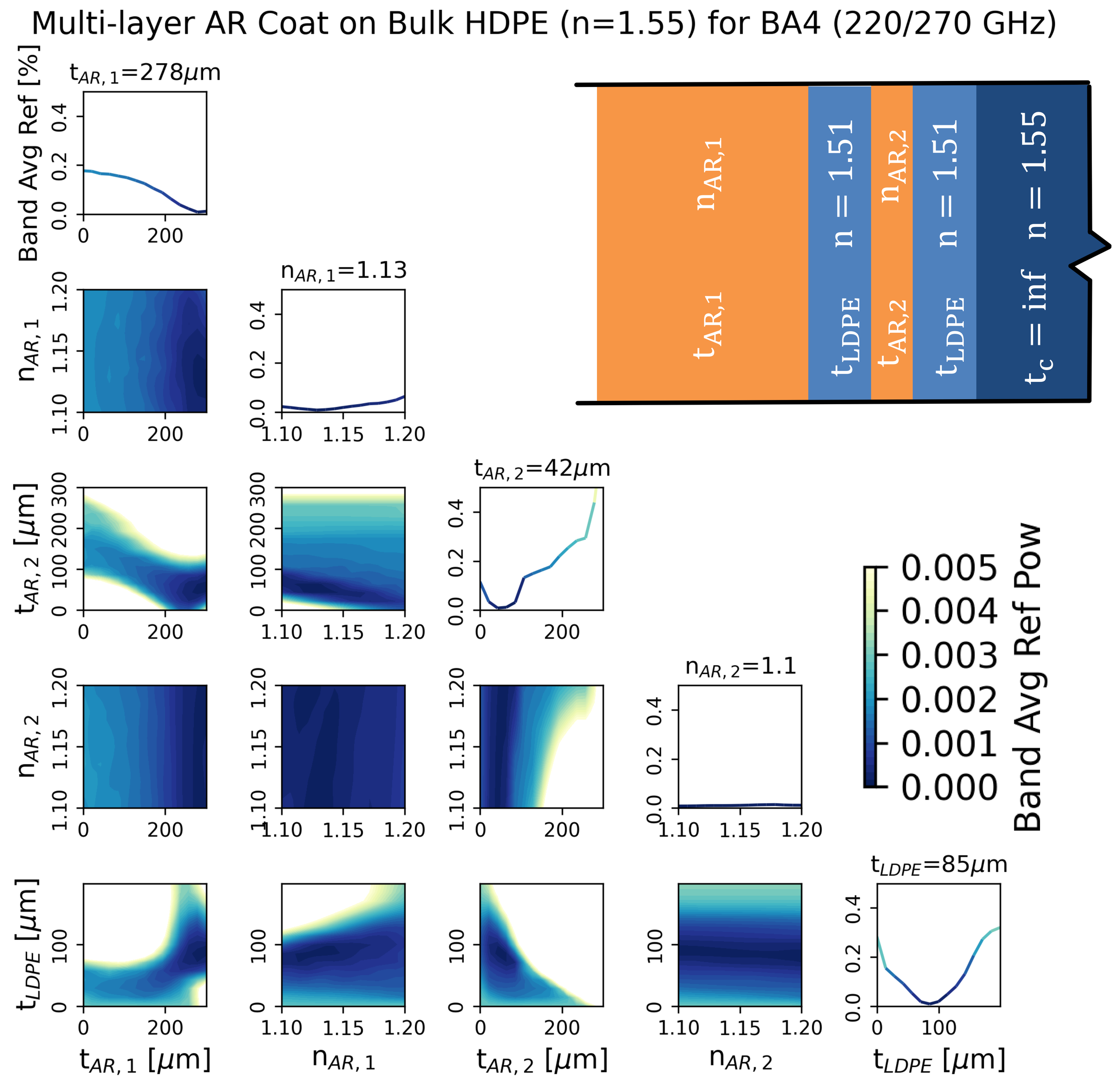

Fig. 2. Design corner plot for multilayer High Frequency (HF) HDPE optics (BA4, 200-300 GHz). Parameters not plotted in each contour are optimized to produce the lowest possible reflection.

Ideal AR Coats

We compare achieved AR coats on recent optics in the current generation of mm-wavelength (BICEP/Keck, wSMA) instruments compared to the ideal Chebyshev AR coats.

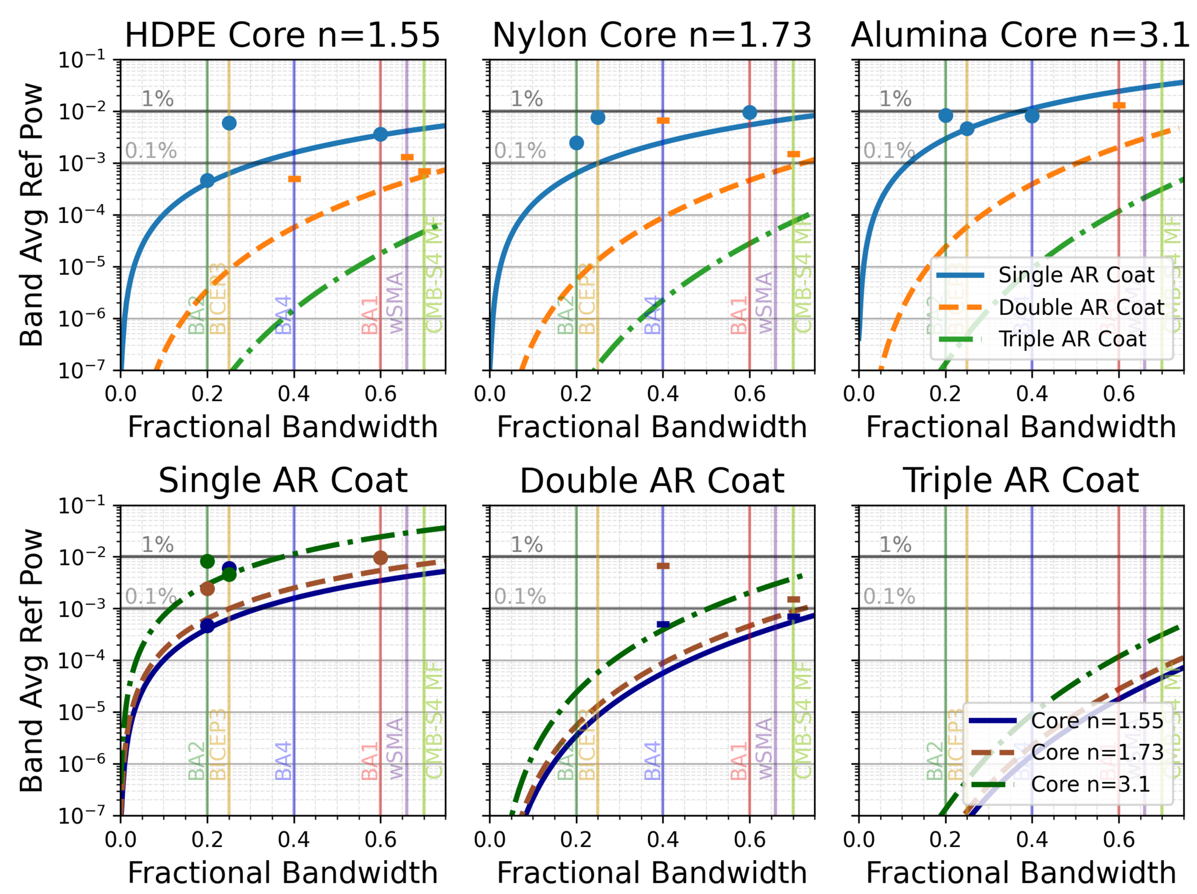

Fig 3. Average in-band reflections for ideal anti-reflection coats on infinitely thick cores of HDPE (n=1.55), nylon (n=1.73) and alumina (n=3.1). Points represent achieved AR coats for each material on each instrument where shape of the point denotes rough equivalent number of layers. Circles are single layer equivalent AR coats, lines are double layer AR coats.

Instrument	BA2	BICEP3	BA4	BA1	wSMA	CMB-S4 MF
Reference	[2]	[3]	[4]	[5]	[6]	[7]
Band Cen. [GHz]	150	95	250	35	285	125
Band Edges [GHz]	135 165	83 107	200 300	25 45	190 380	75 165
¼ Wavelen. [μm]	500	790	300	2140	260	600

Table 1. Relevant reference, band centers, band edges, and quarter wavelengths for each of the bands in Fig.3.

DeWAL: Stackable ePTFE

The bands most difficult to source materials for are the highest frequencies: finding a material that keeps an electrical length to within a few percent of 300 μm over large areas (BICEP Array aperture diameter ~70 cm) is hard. DeWAL presents a unique solution.

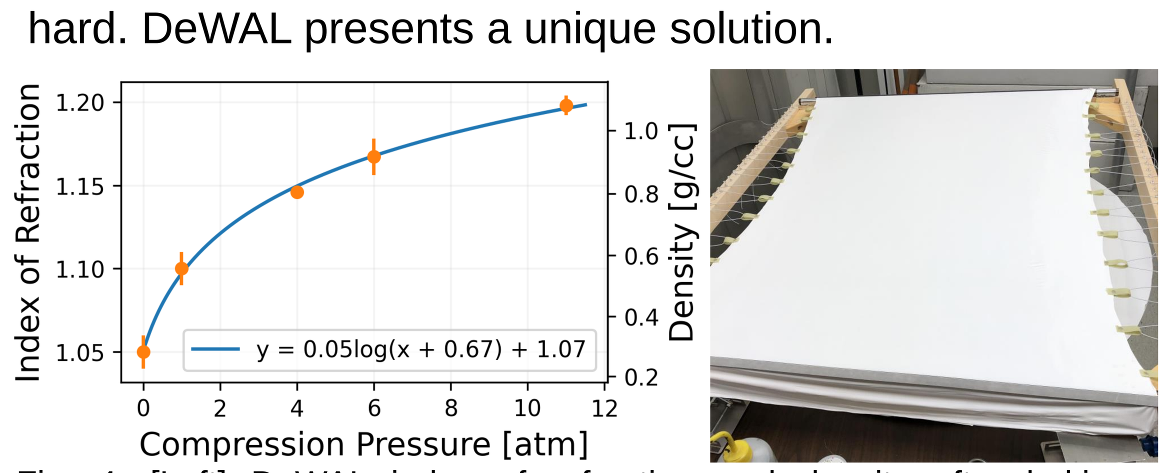

Fig. 4. [Left] DeWAL index of refraction and density after baking at pressures between 0 and 11 atm. [Right] DeWAL sheet in stretching rig.

DeWAL is a stackable ePTFE membrane: when layers are compressed together under at least 3 atm of pressure, they stick with peel strengths ~2 times stronger than layers compressed at 1 atm of pressure. This allows us to generate very thin, low-density layers.

Baking Pressure [atm]	1	3	10
Initial Thickness [μm]	158	152	156
Final Thickness [μm]	60	45	30
Peel Strength [g/cm]	2.4	4.9	6.9

Table 2. Thicknesses and peel strengths of two layer DeWAL stacks baked at 1, 3 and 10 atm and 135° C for eight hours.

Achieved AR Coats

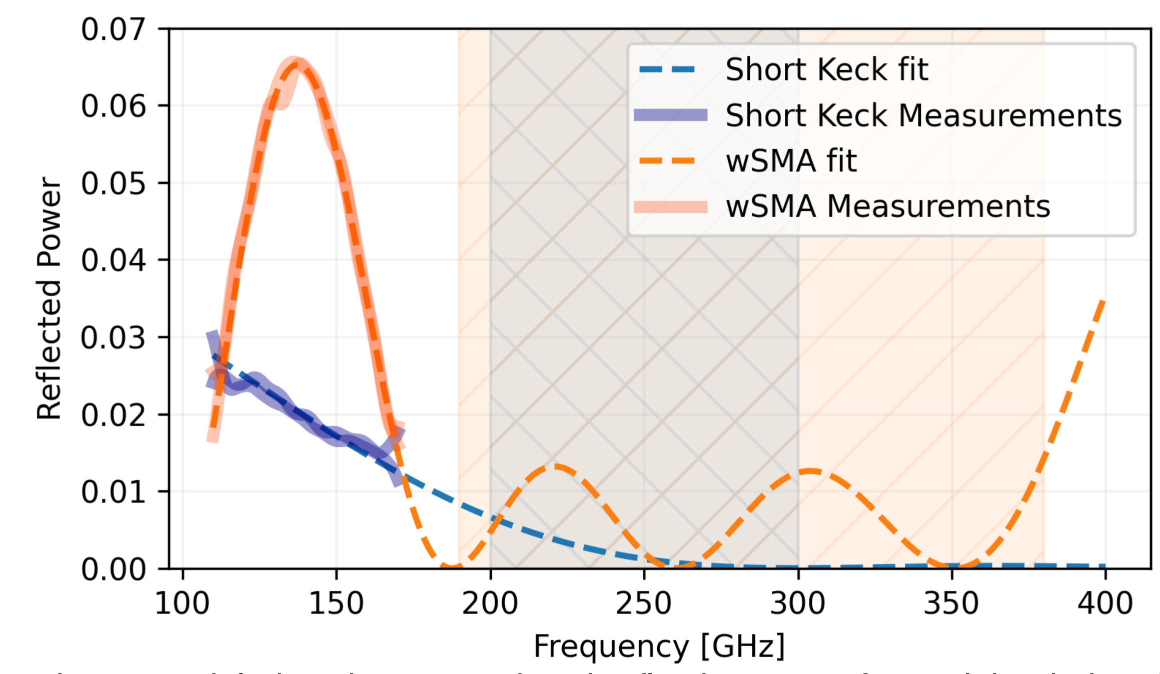

Fig. 5. Modeled and measured anti-reflection coats for a slab window for high frequencies (Short Keck) in blue and a thin window (wSMA) in orange. The bands are similarly color coded. Solid lines are measurements, dashed lines are fits. The slab Short Keck measurements are a single incidence reflection, while the wSMA measurements are reflections off all layers.

We have produced successful anti-reflection (AR) coats for the two highest frequency bands in Table 1 using stacked DeWAL. Multiple layers of DeWAL combined with adhesion layers of LDPE can combine into a 'pseudo-layer' with electrical length similar to a quarter wavelength.

Core	t_{DW1} [μm]	t_{LD1} [μm]	t_{DW2} [μm]	t_{LD2} [μm]	t_{DW3} [μm]
HDPE 1.5" (Short Keck)	200	60	40		
HMPE 0.7 mm (wSMA)	200	40	20	60	40

Table 3. Physical thicknesses of each AR layer for the AR coats in Fig 5. DeWAL (DW) layers have an index of 1.12, and LDPE (LD) adhesion layers have an index of 1.51.

Conclusions

1. **The lowest possible band average reflection with finite number of quarter wavelength layers can be found with Chebyshev polynomials.**
2. **DeWAL (a thin ePTFE membrane) can be stacked and compressed into a thicker combined layer.**
3. **Multi-layer stacks of DeWAL and LDPE can produce anti-reflection coats for broadband high frequency millimeter receivers.**
4. **Improved control of the parameters for anti-reflection coat layers produces coats that can perform similarly to the ideal Chebyshev solution.**
5. **Produced anti-reflection coats on PE cores for high frequency mm bands that generate less than 0.7% band average reflected power.**

References

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