

Lecture 15: Color Sensing

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Computer Imaging & Graphics

The Roadmap

Theoretical Preliminaries

Human Visual Systems

Digital Camera Imaging

Modeling and Rendering



Photographic Optics

Image Sensor

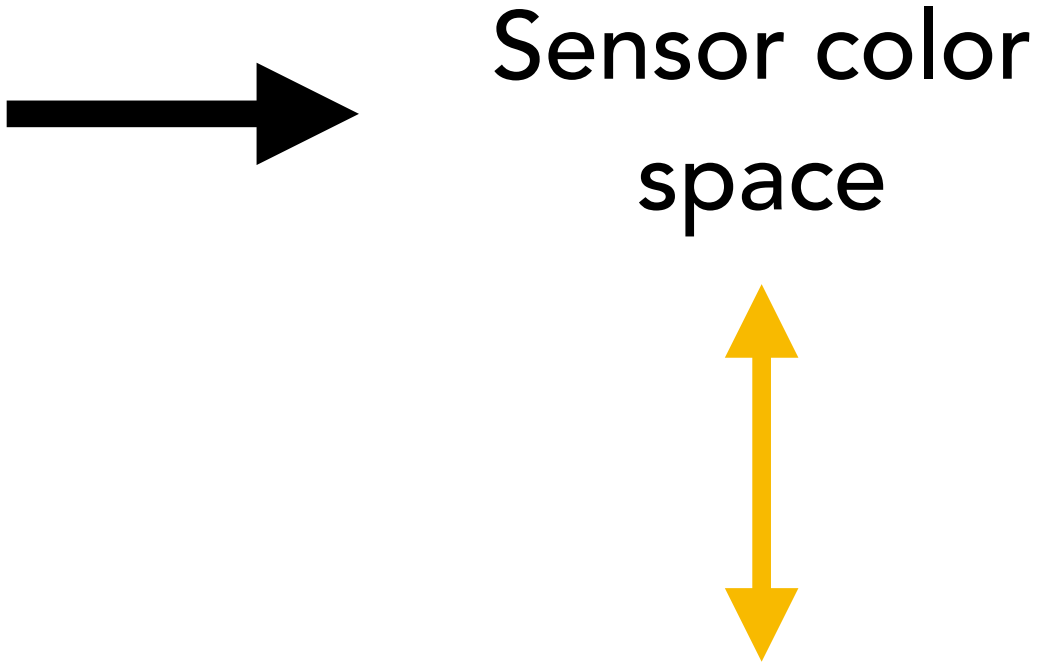
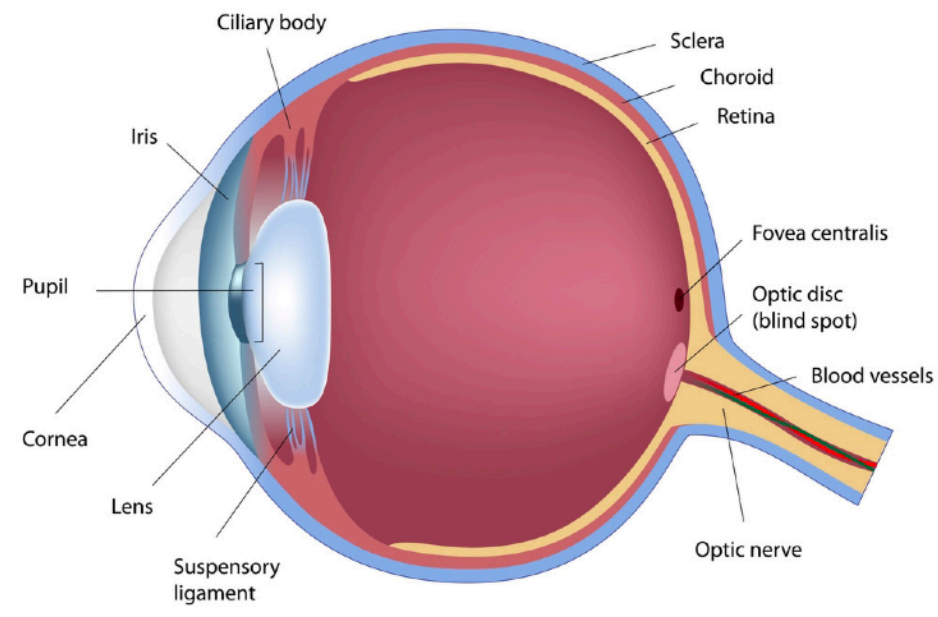
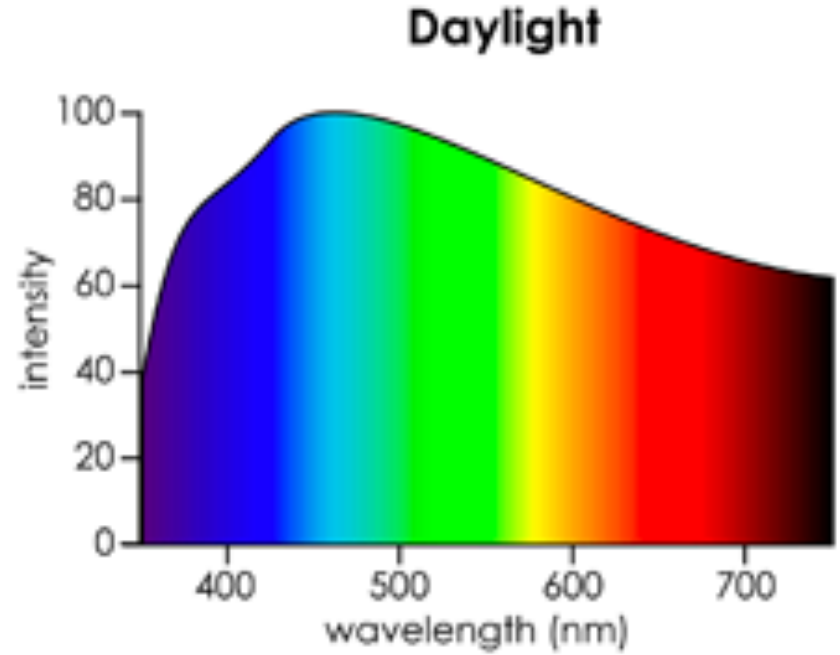
Image Signal Processing

Image/Video Compression

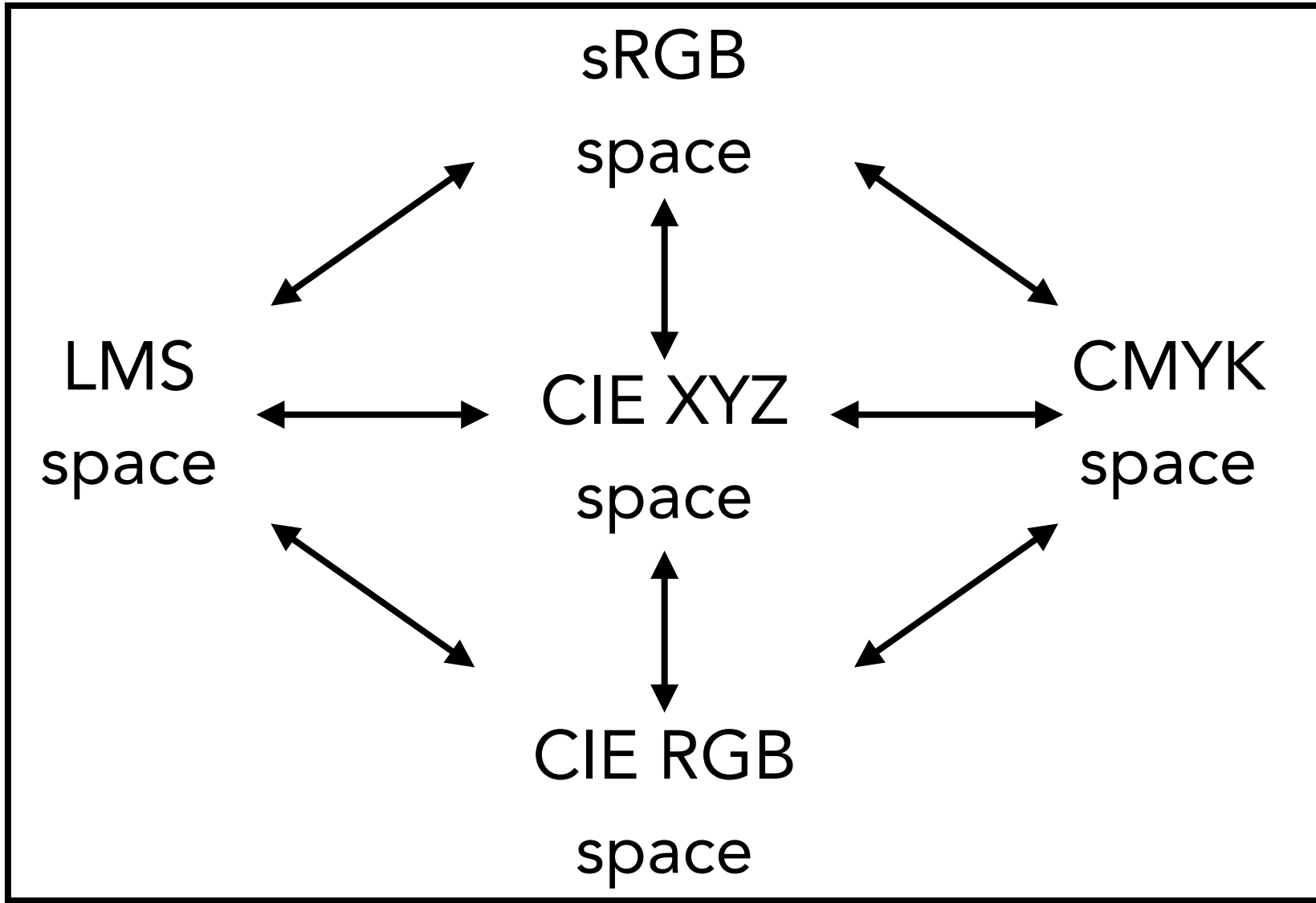
Immersive Content

Goal of Color Sensing

What if this is not true? Metamers in human vision would *not* be metamers in camera vision: colors appearing different to your eyes would look the same in photos and vice versa.



Cone responses



<https://9to5mac.com/2017/12/07/iphone-flickr-most-used-camera/>
<https://www.eyeworld.org/research-finds-human-visual-cortex-continues-development-mid-30s>

How to Sense Color?

Principle of **univariance**: once a photon is converted to an electron, we lose wavelength/color information (there is no red electron vs. blue electron).

How do humans sensor color? We have **three** types of cones, each has a different **spectral sensitivity** to light.

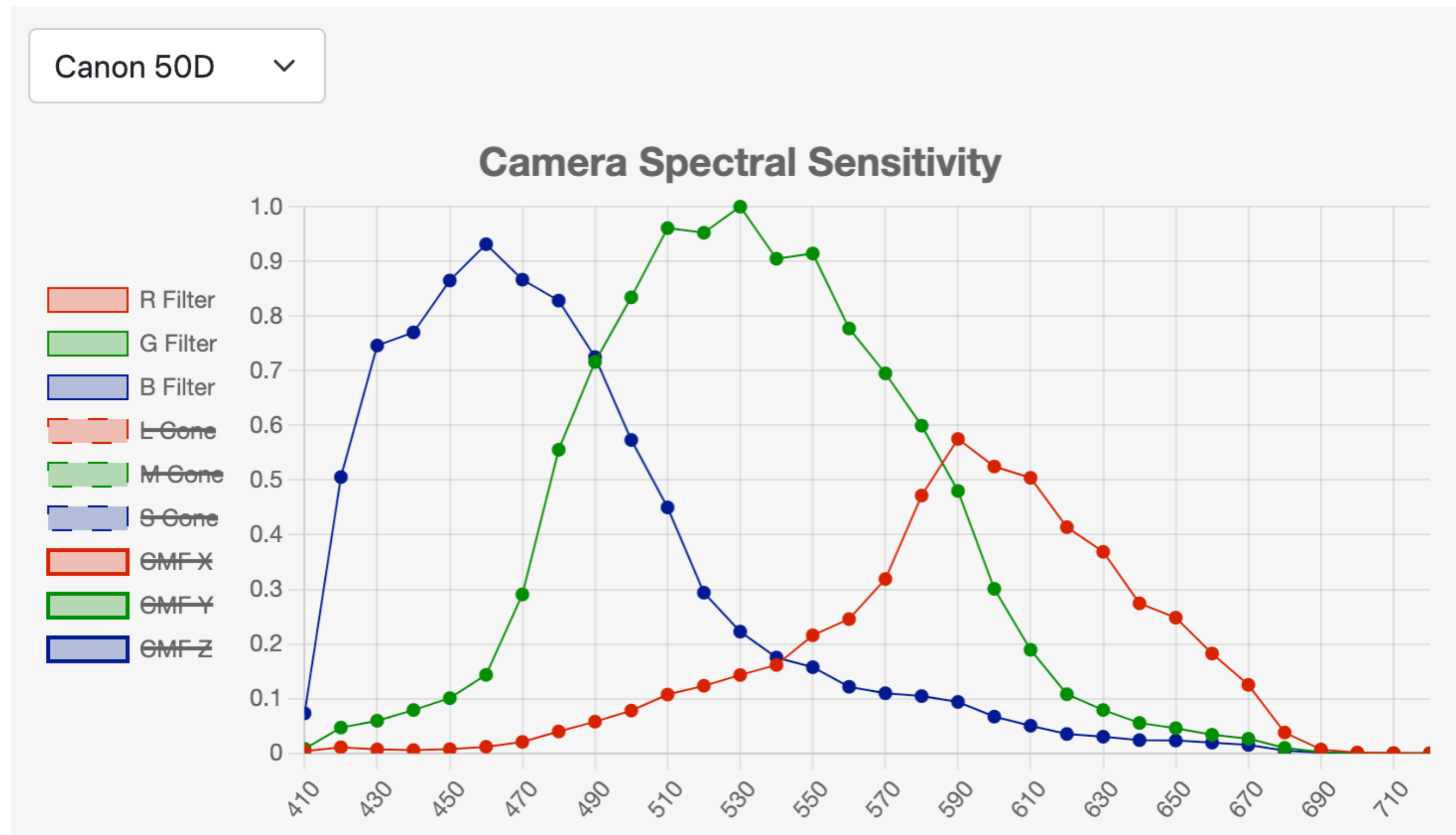
- Light spectrum gets transformed to three numbers (L, M, S cone responses, or equivalently the tristimulus values in a color space).

Cameras also need to somehow generate three numbers from light too.

The three values should ideally be the same as the LMS cone responses.

- Or can be converted to tristimulus values in one of the known color spaces.

Sensor Spectral Sensitivity

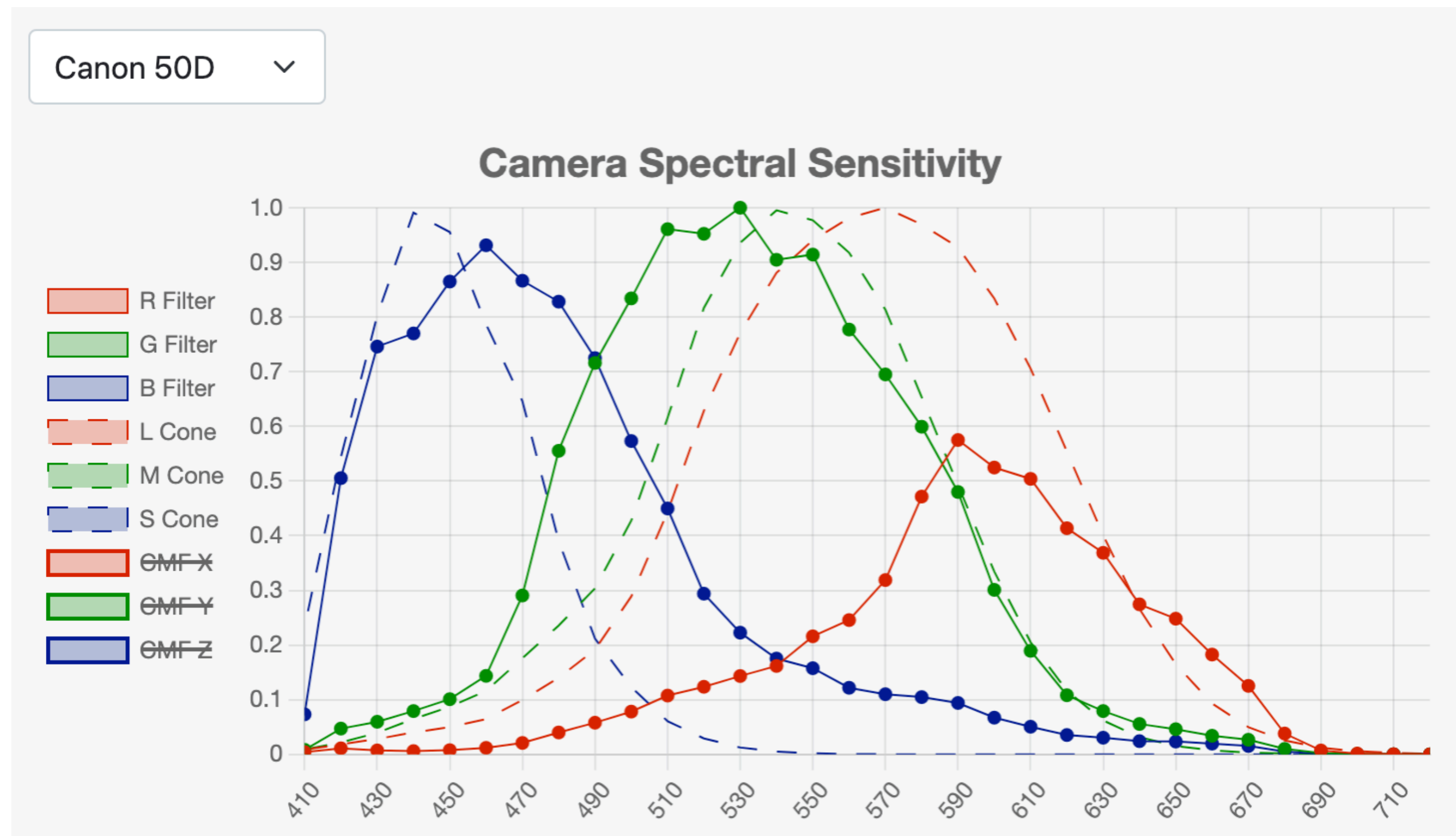


Effectively we need to have three kinds of sensors, each has a unique *spectral sensitivity function* (SSF).

SSF(λ): generated electrical energy per unit incident light energy at a given λ .

<https://horizon-lab.org/colorvis/camcolor.html>

Sensor Spectral Sensitivity

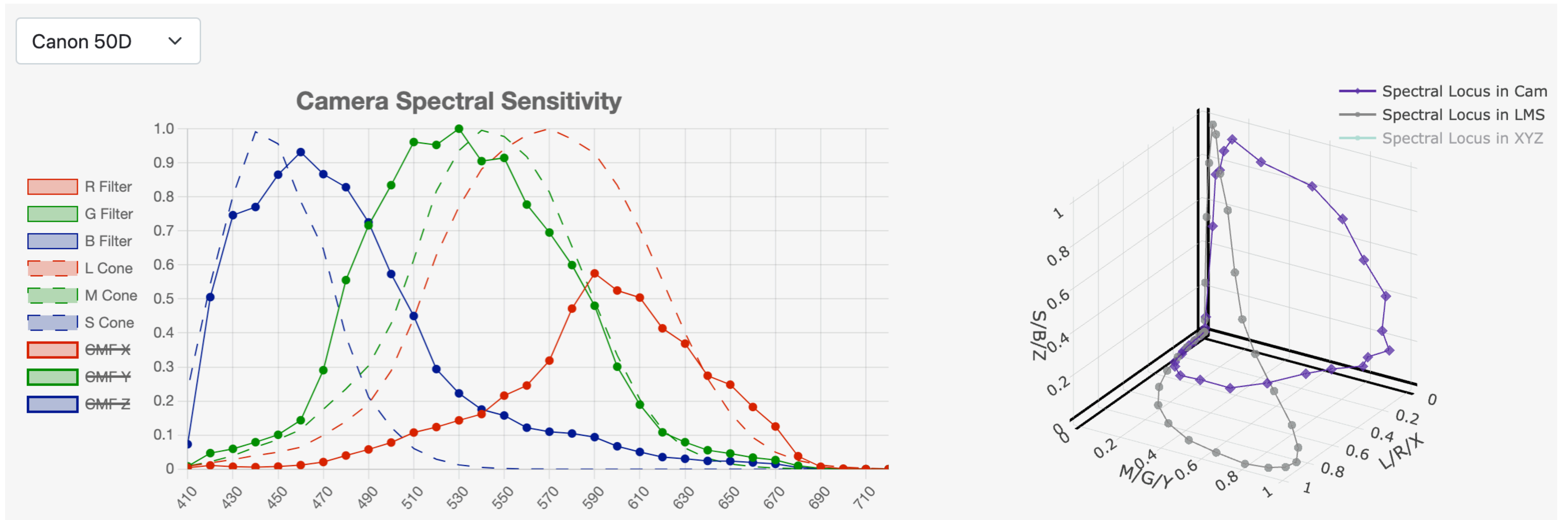


How should SSFs look like?

- **Ideally:** each sensor's SSF mimics LMS and XYZ, since CMFs in other color space usually involve negative values that are physically unrealizable.
- **Reality:** hard to be exact. SSF depends on lots of things (sensor quantum efficiency, microlens, filters, manufacturability, etc.).

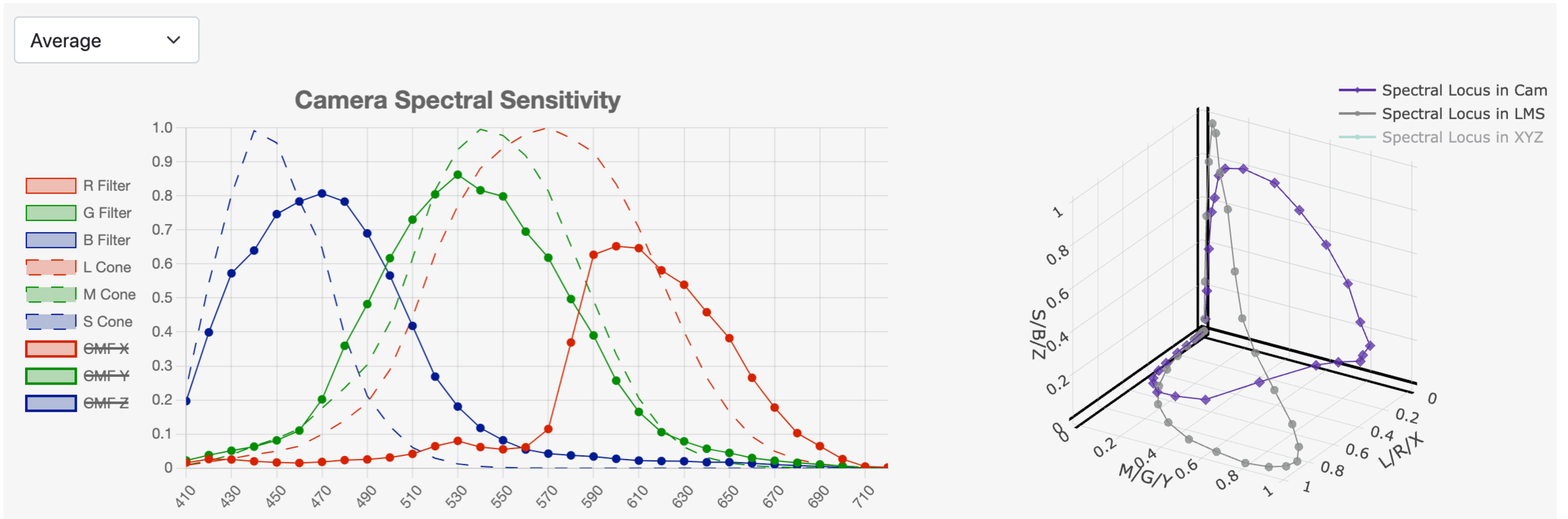
<https://horizon-lab.org/colorvis/camcolor.html>

Sensor Spectral Sensitivity



<https://horizon-lab.org/colorvis/camcolor.html>

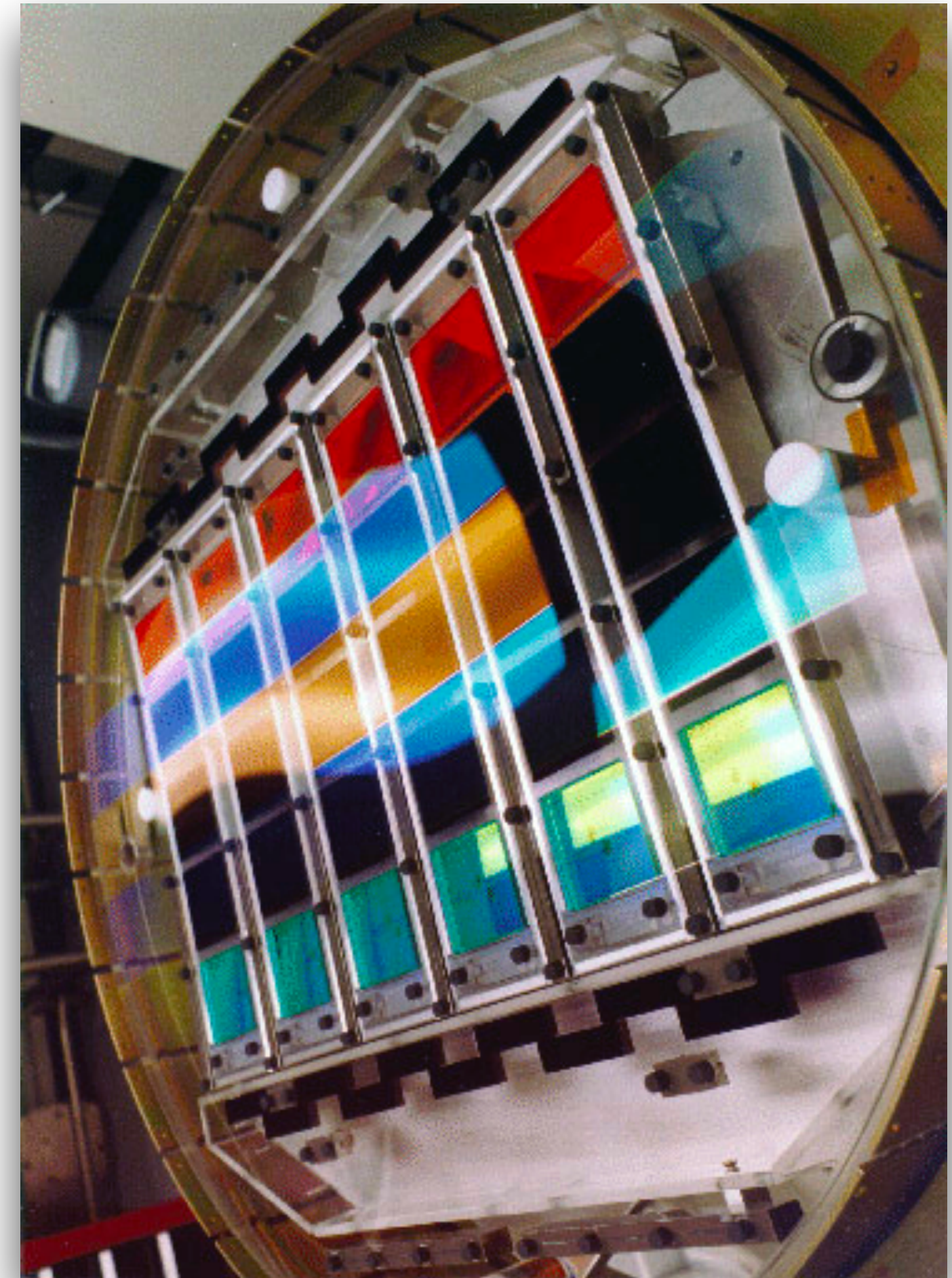
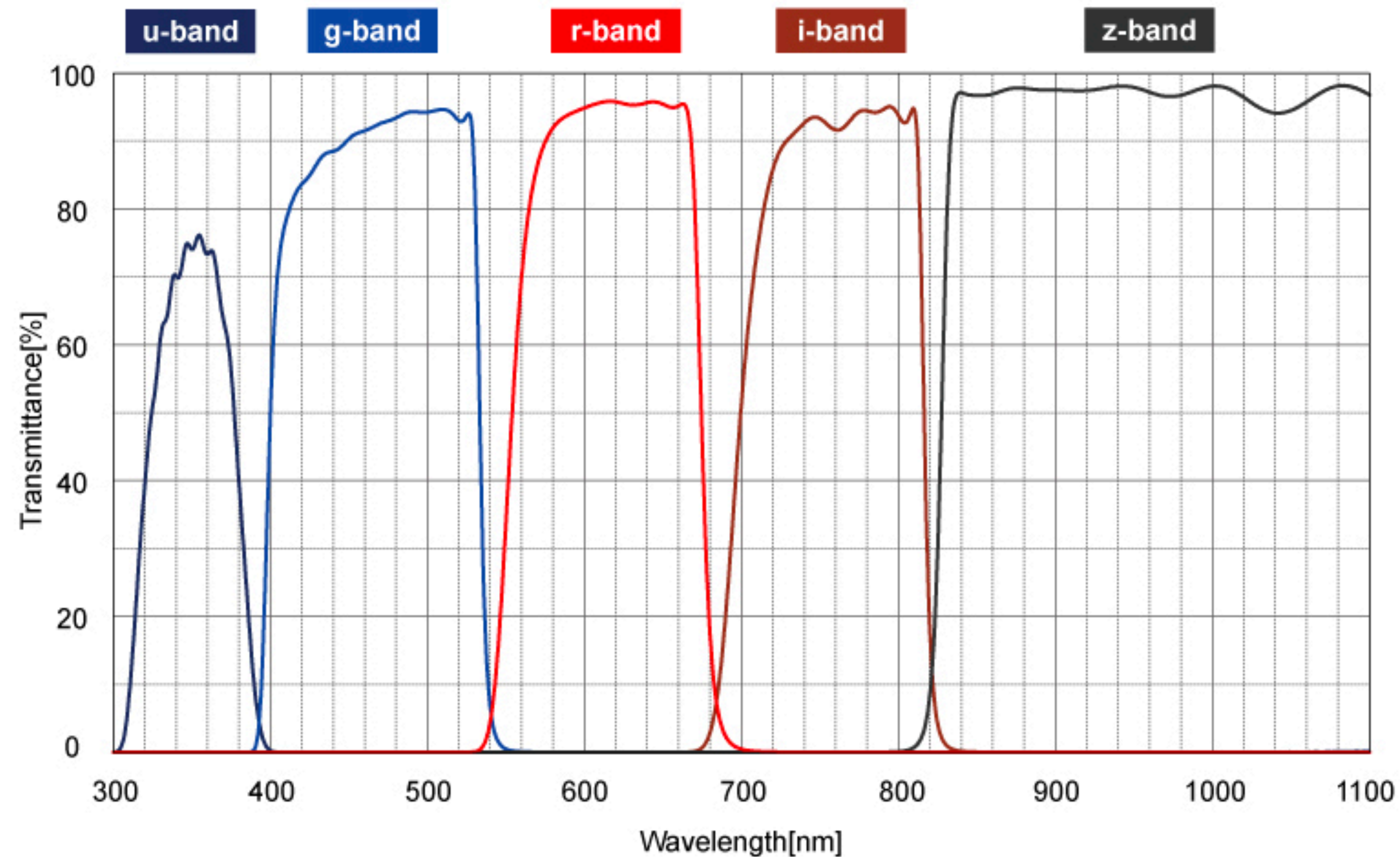
Sensor Spectral Sensitivity



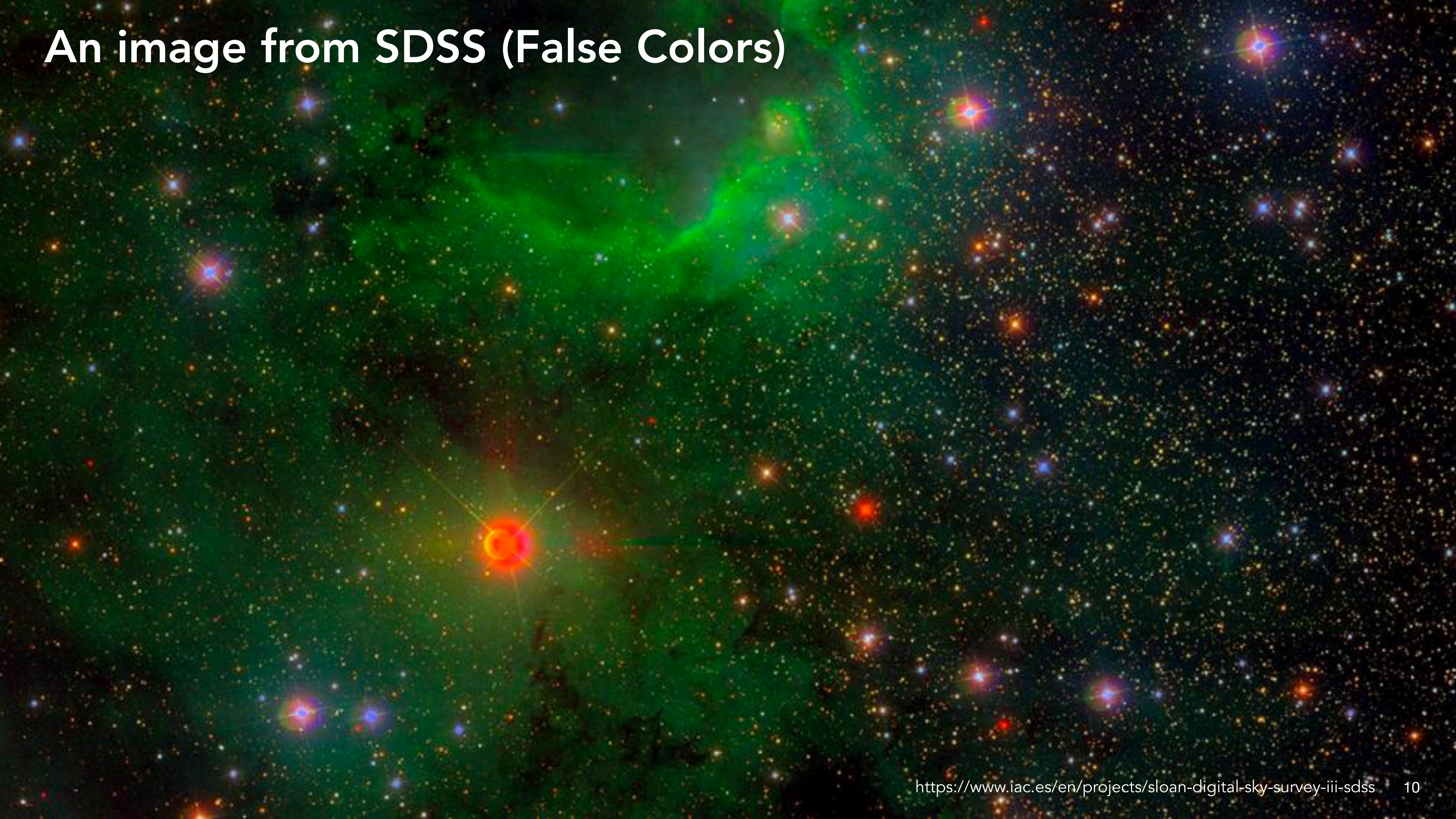
<https://horizon-lab.org/colorvis/camcolor.html>

Astrophysical Imaging Uses More Filters

Spectral transmittance of the five filters in the first SDSS camera

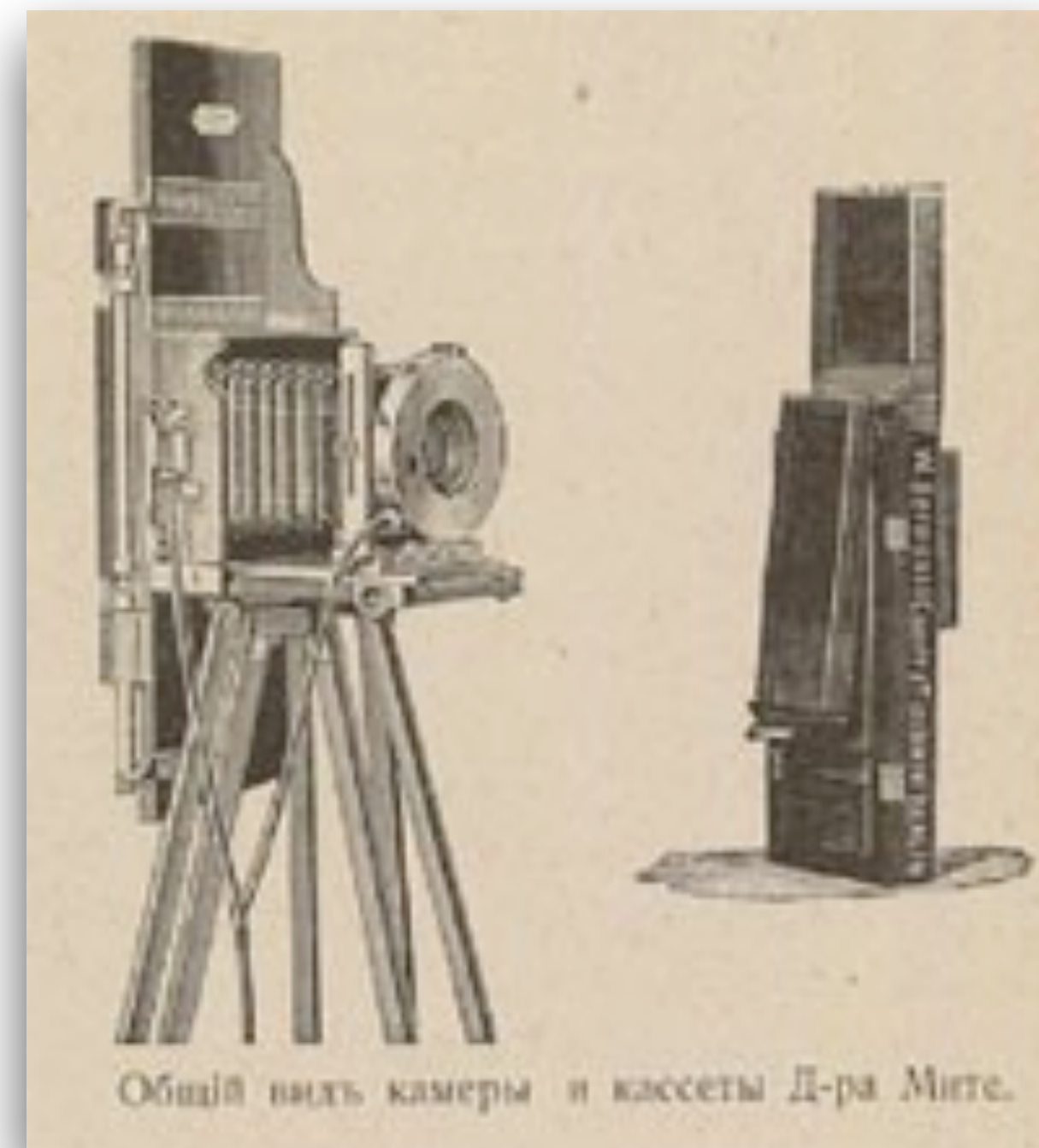


An image from SDSS (False Colors)



Realizing “Three Kinds of Sensors”

Take Three Separate Shots and Combined Them



1906 by Dr. Adolf Miethe



Sergey Prokudin-Gorsky
(1836 — 1944)

Use Three Sensors

Use three sensors

Similar to "three shots" (previous slide)

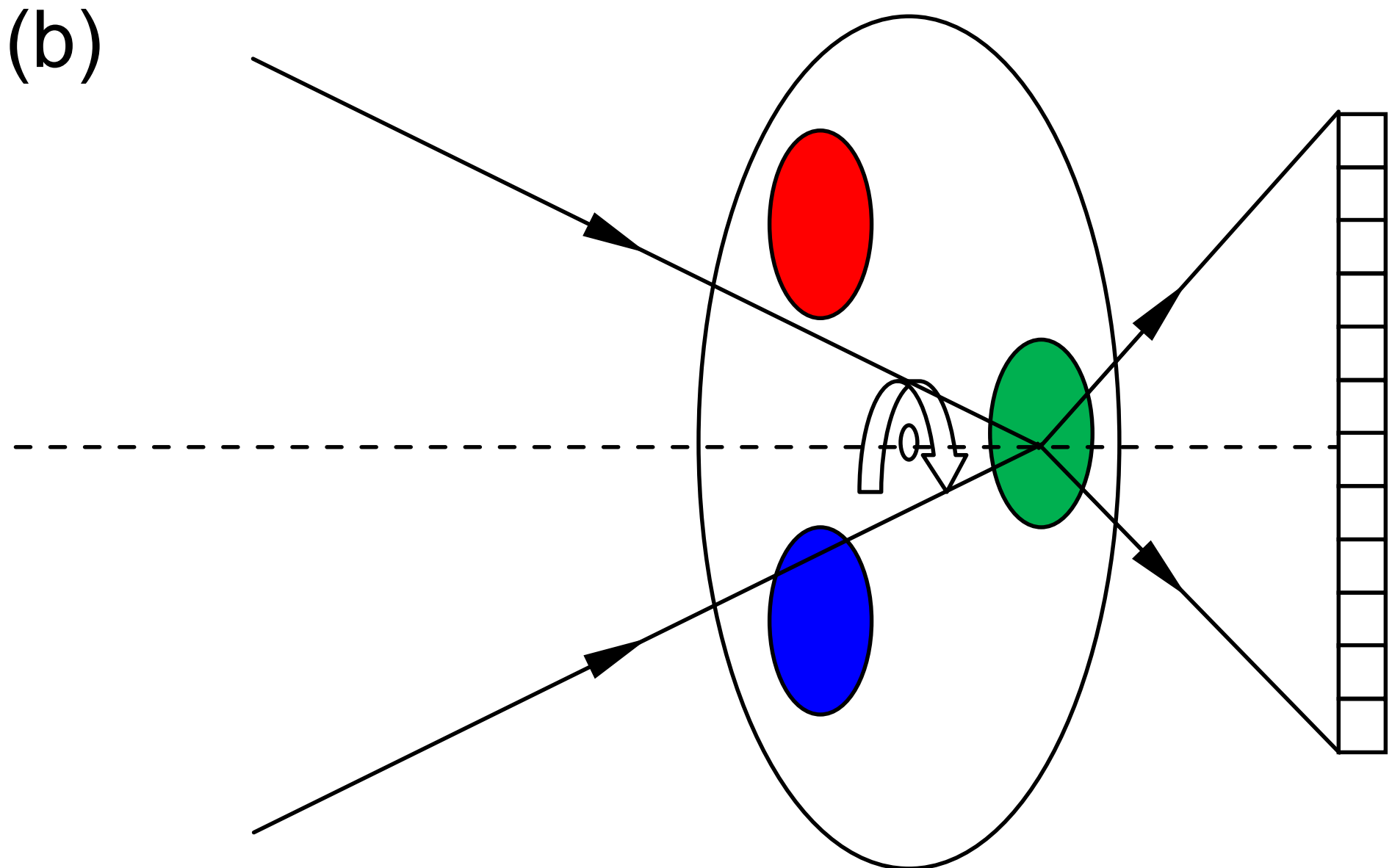
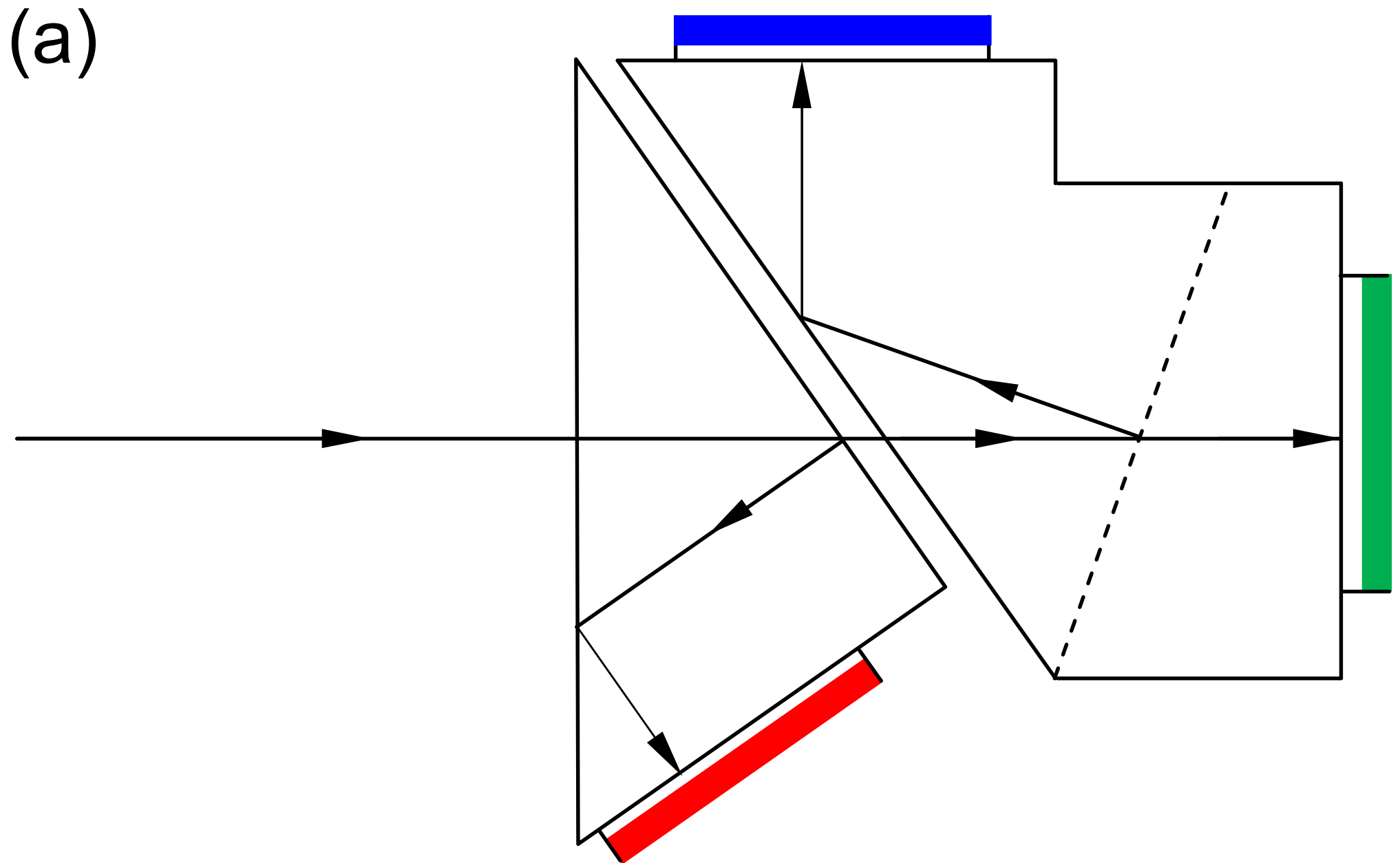


Figure 14.3 (a) Three-sensor camera. (b) Sequential colour camera.

Use Three Sensors

Use three sensors

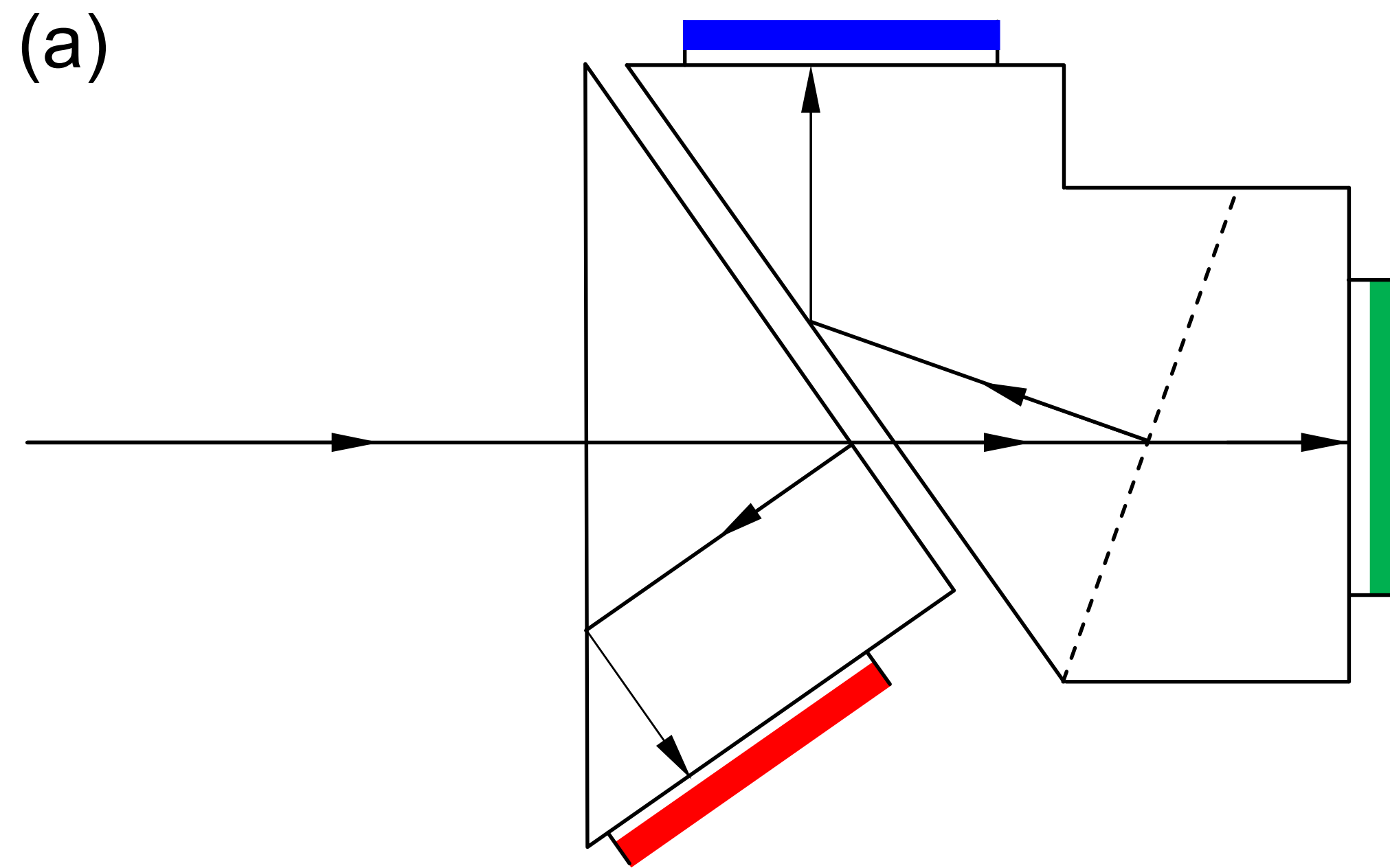
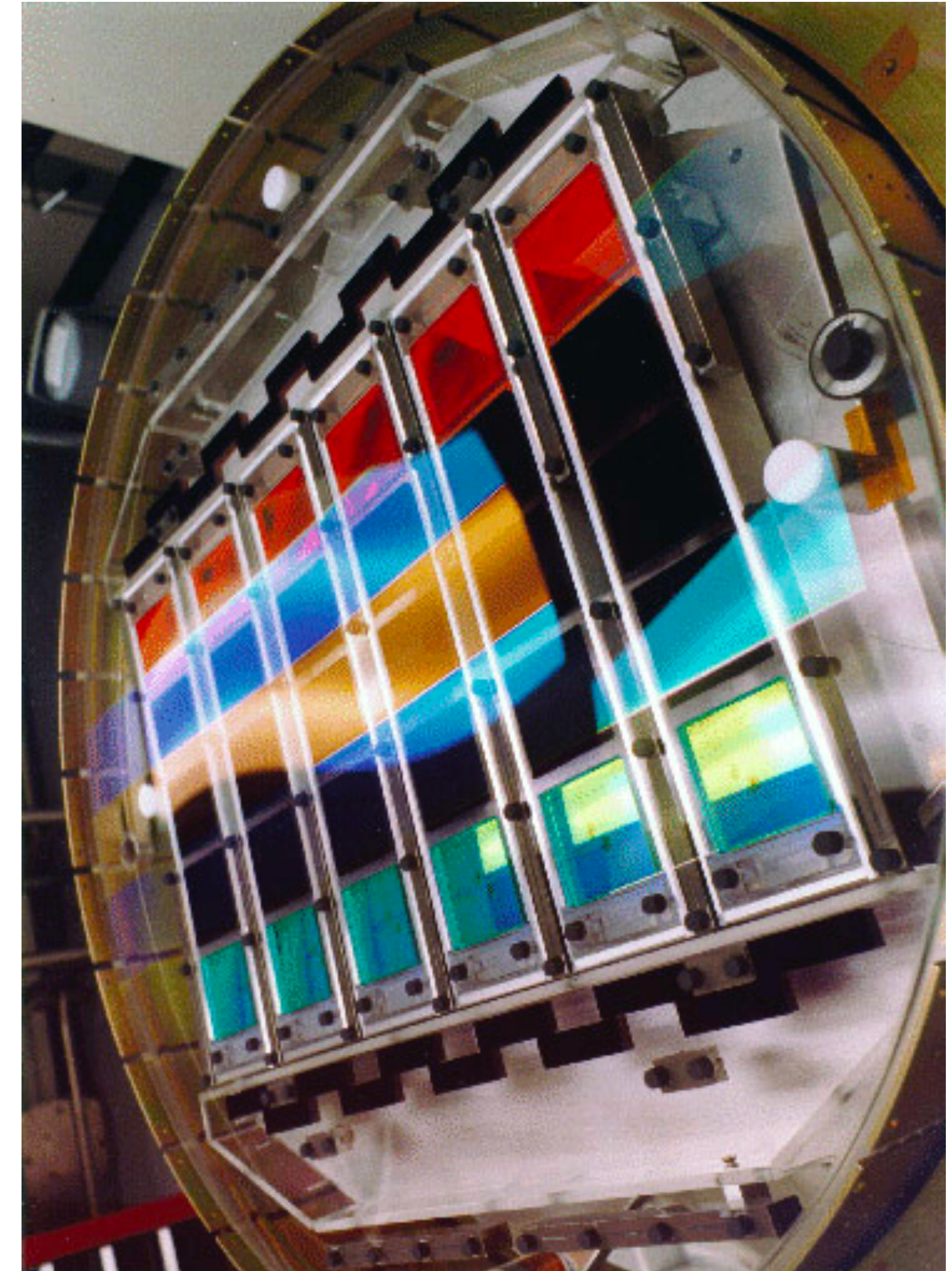
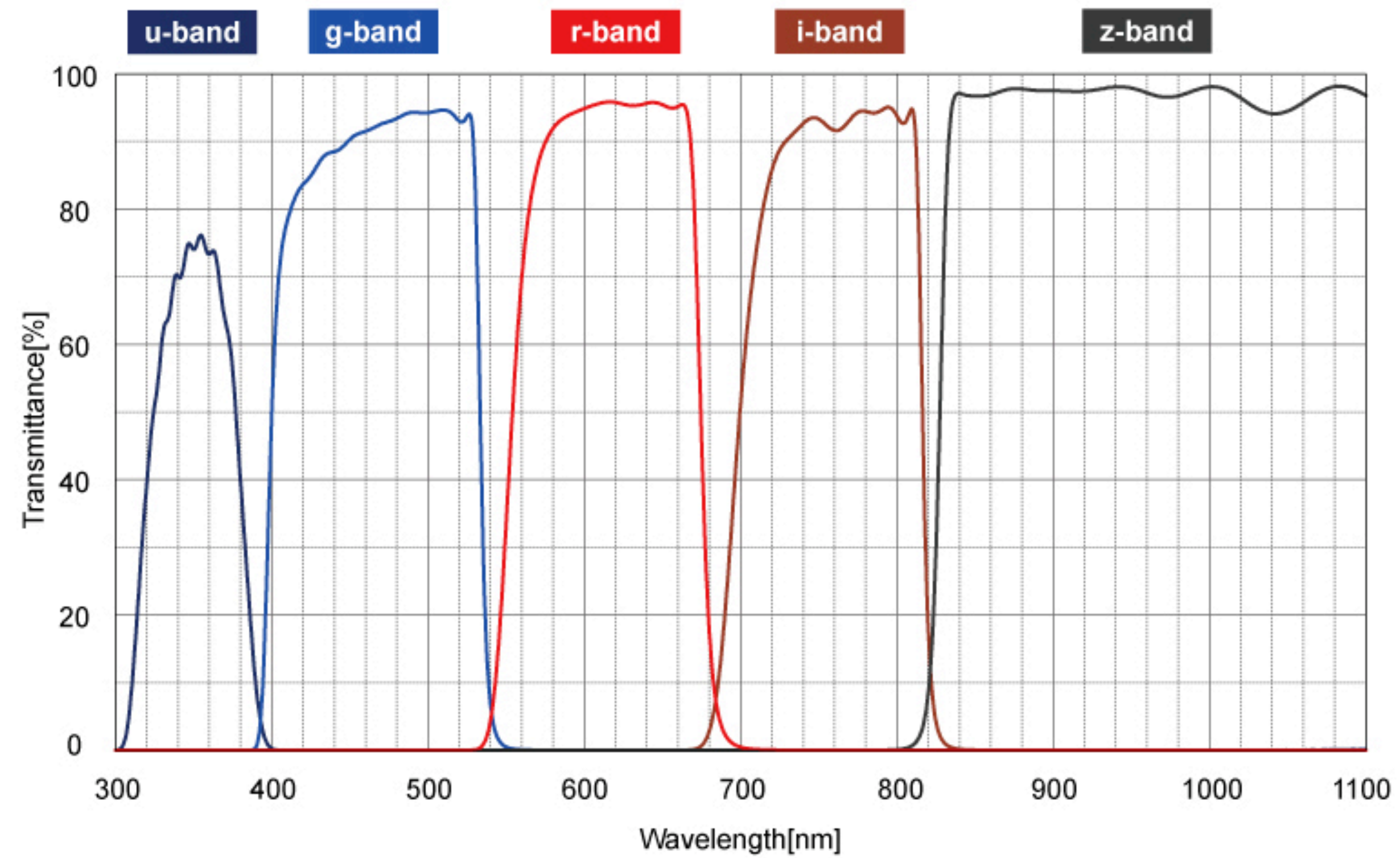


Figure 14.3 (a) Three-sensor camera. (b) Sequential colour camera.

Multi-Chip Sensing in Astrophysics



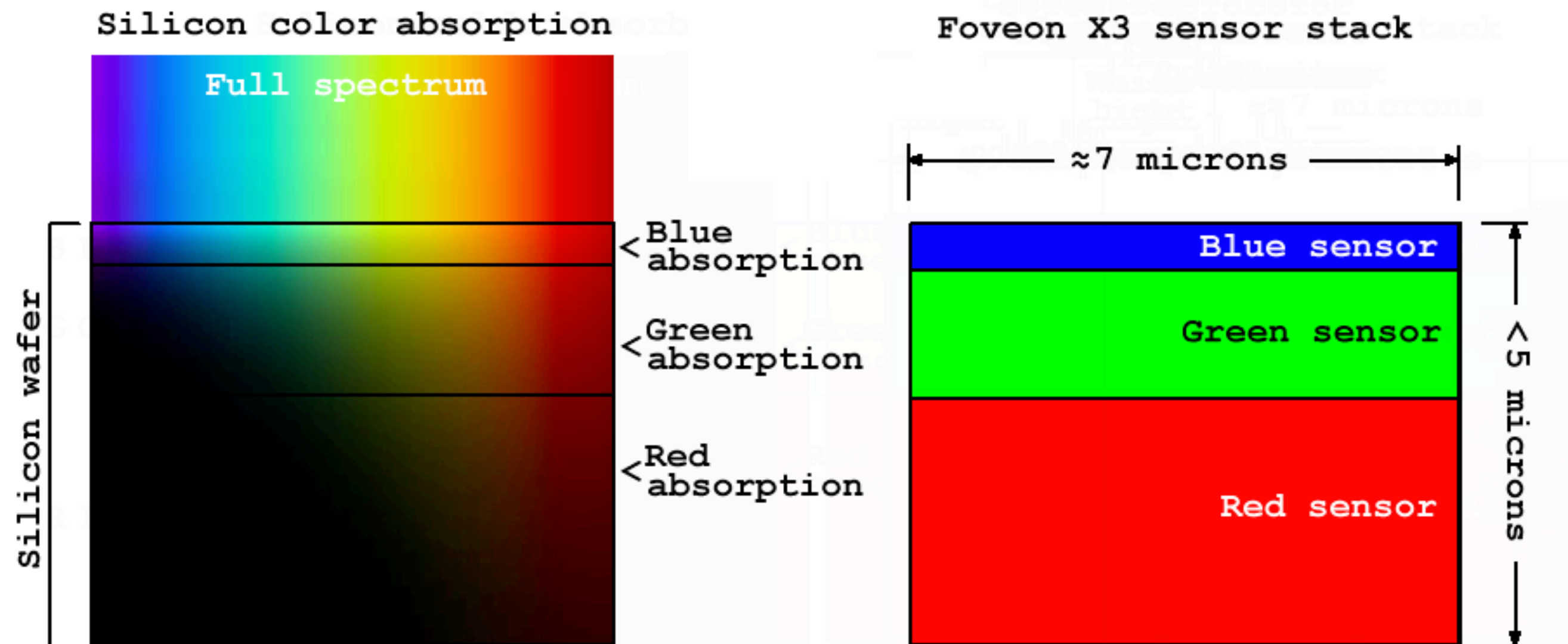
Vertical Stacking

Longer-wavelength light penetrates deeper into silicon.

$$\text{Sensitivity(B)} = \text{Absorption(B)}$$

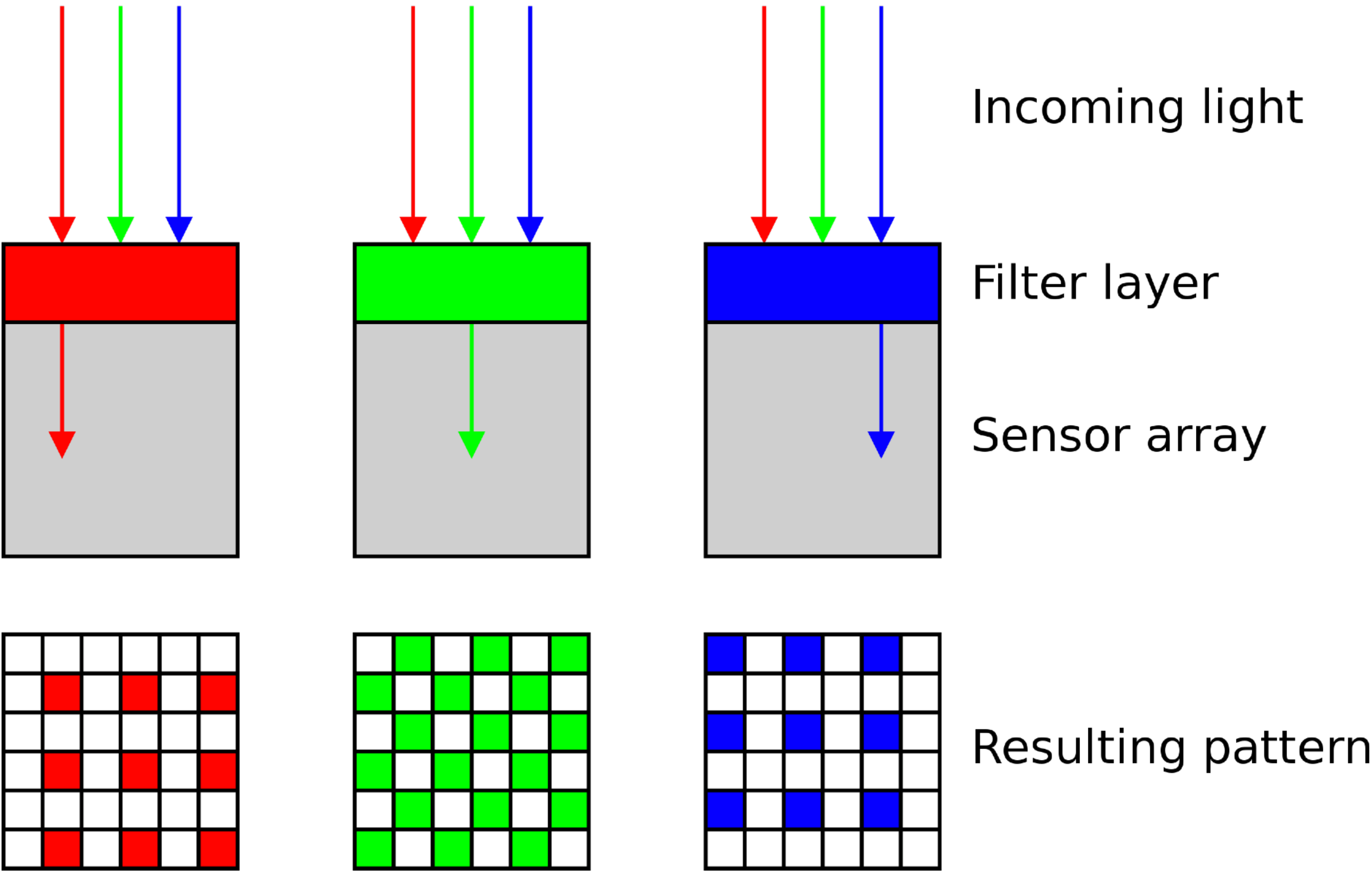
$$\text{Sensitivity(G)} = \text{Transmittance(B)} \times \text{Absorption(G)}$$

$$\text{Sensitivity(R)} = \text{Transmittance(B)} \times \text{Transmittance(G)} \times \text{Absorption(R)}$$

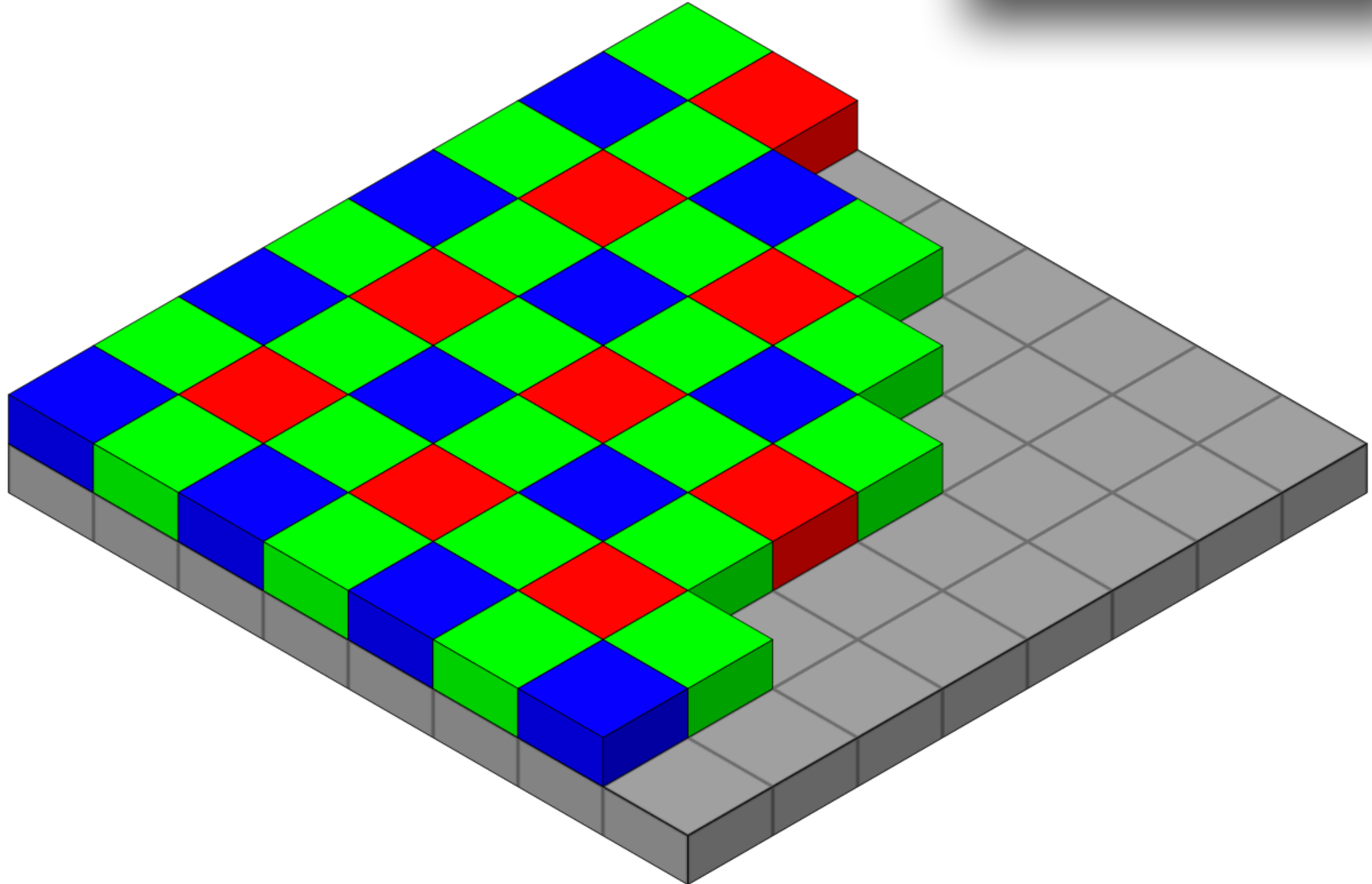




Color Filtering Array



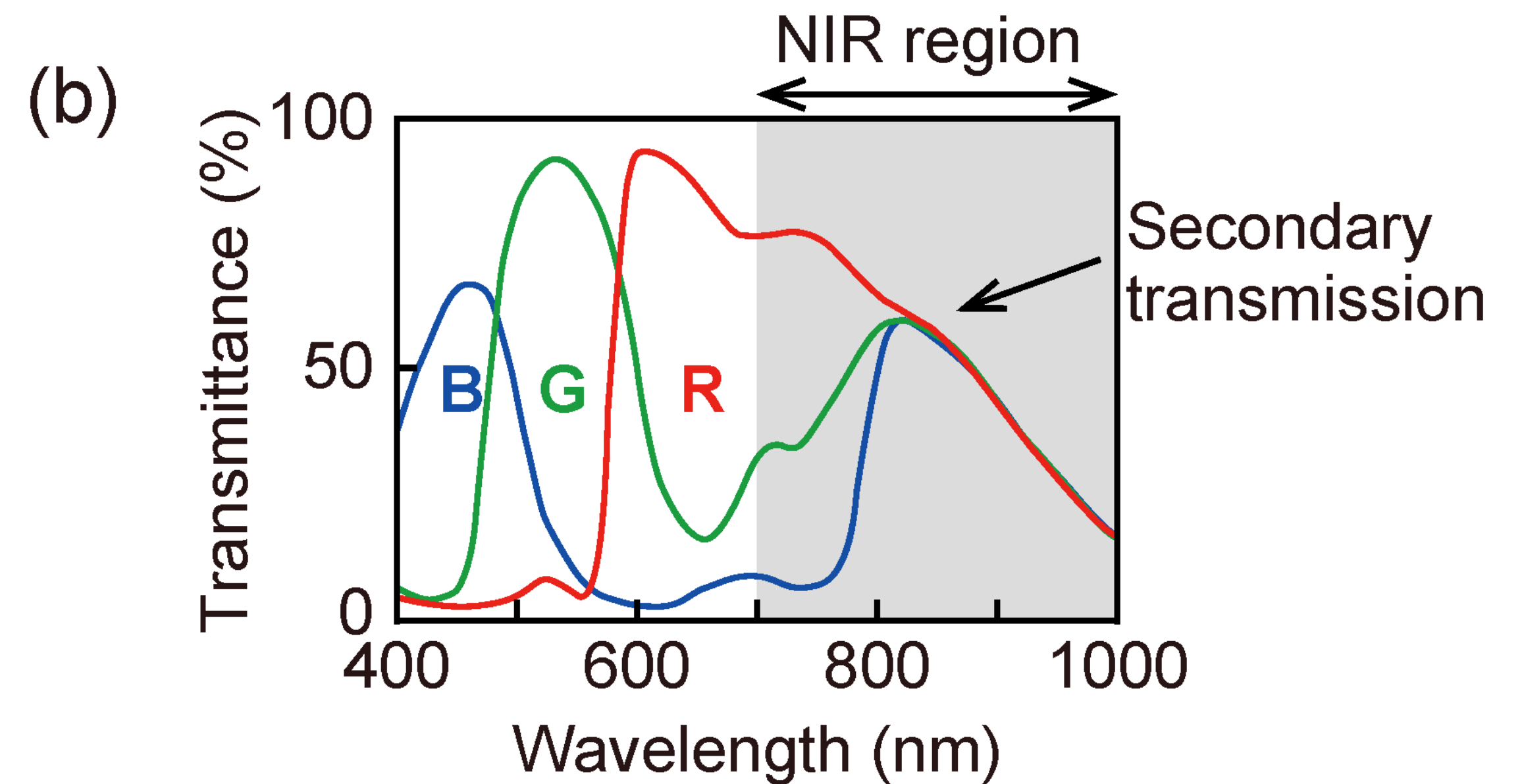
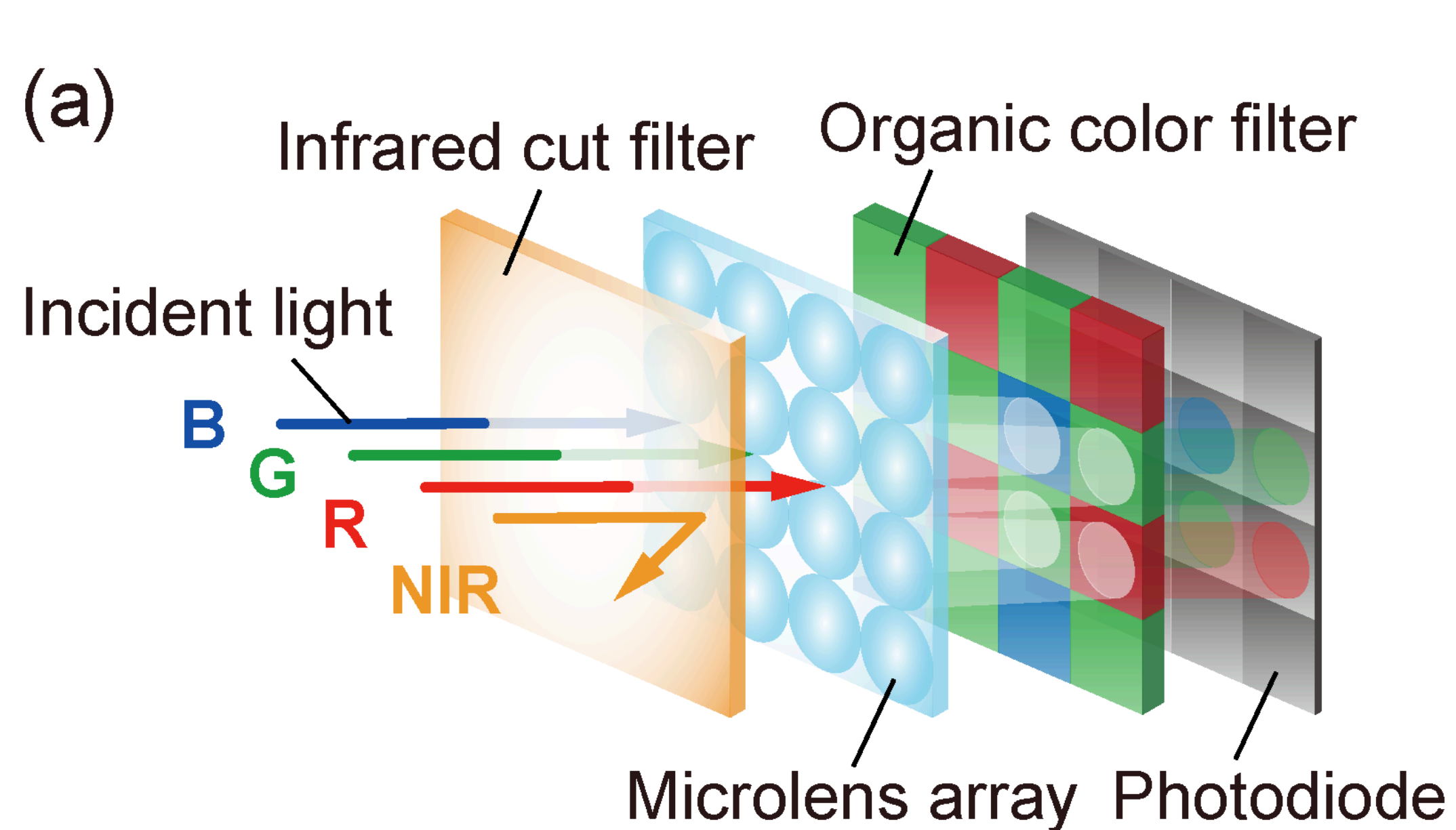
Bayer Pattern



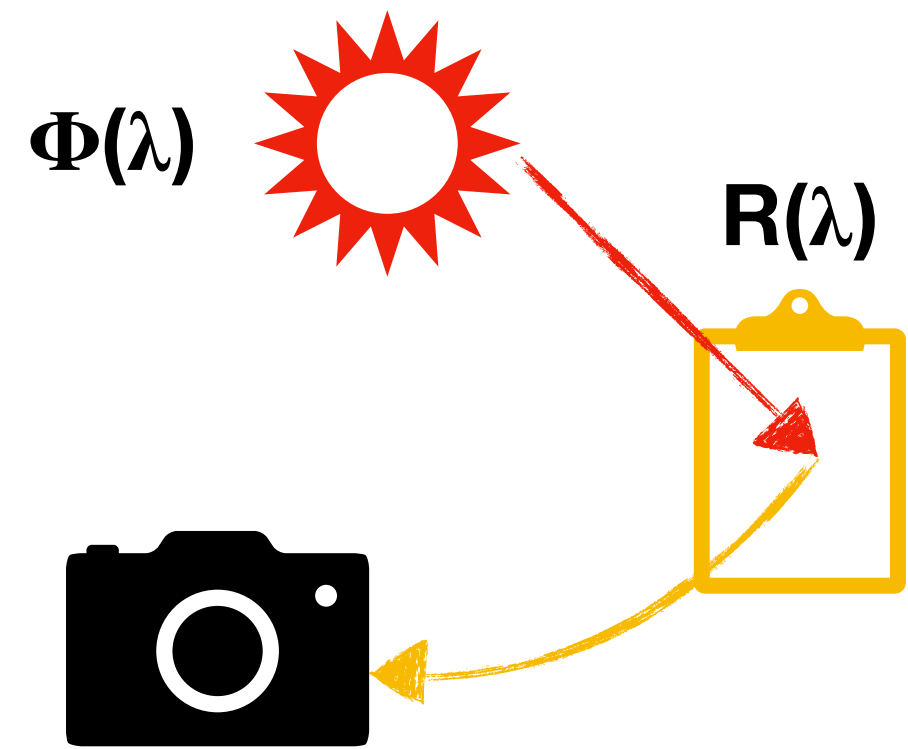


Color Filtering Array

Each filter has a unique **spectral transmittance function**, which characterizes the percentage of photons that can get through at each wavelength.

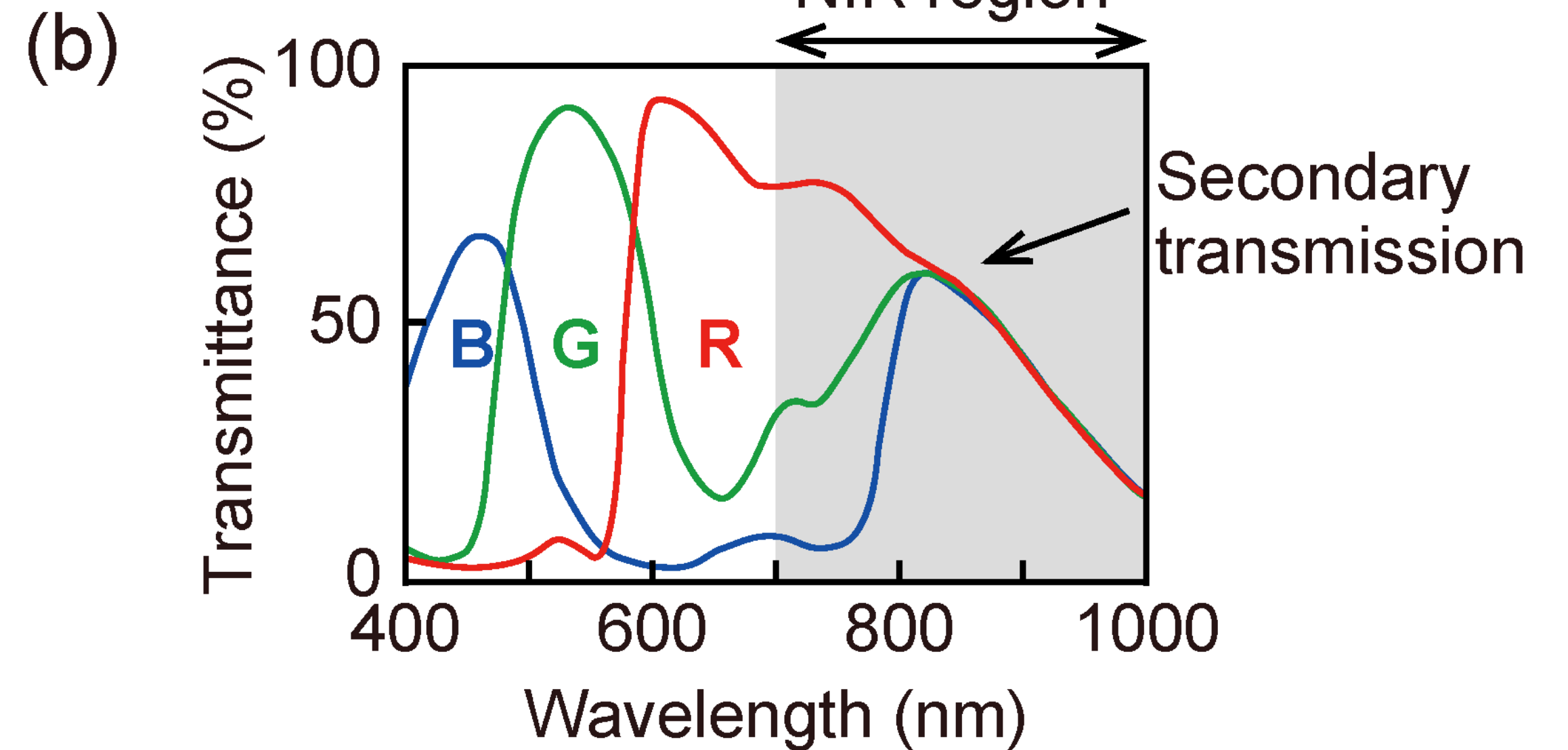
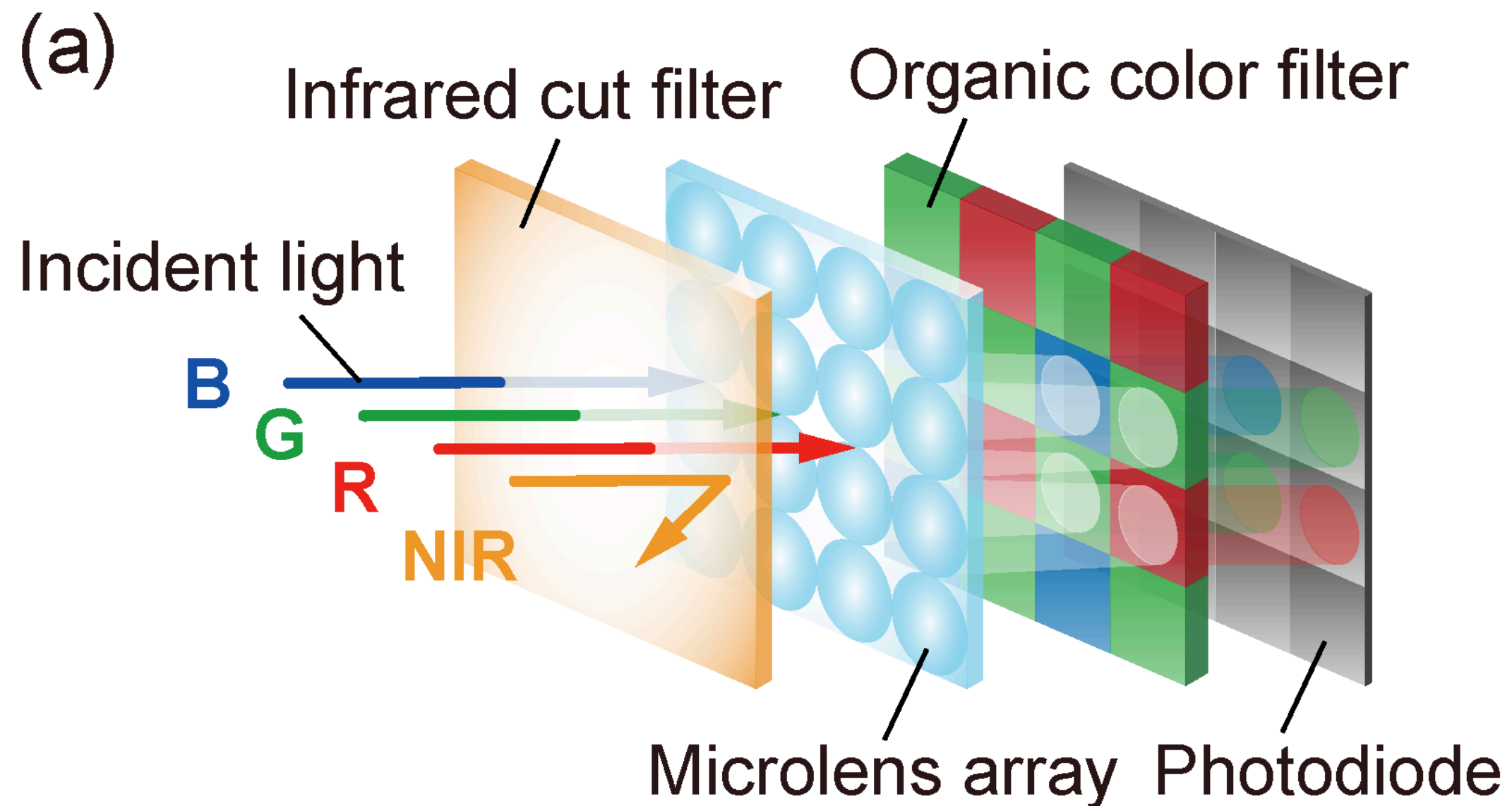


Filters Dim Lights



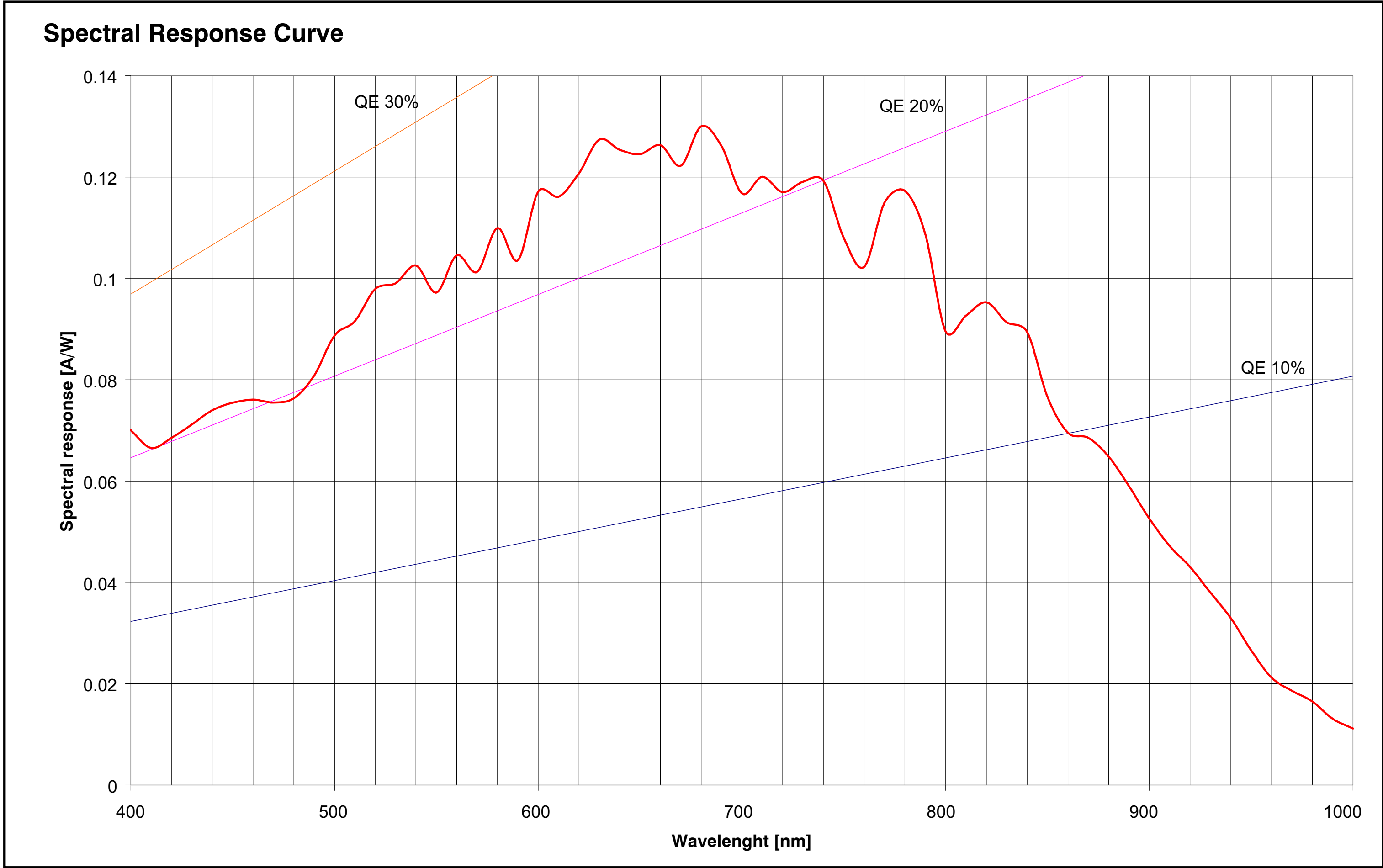
$$Y_R(x, y) = \int_{\lambda} \Phi(\lambda) R(\lambda) IR(\lambda) M(\lambda) CFA_R(\lambda) d\lambda$$

$\Phi(\lambda)$: Spectral transmittance of the micro-lenses
 $R(\lambda)$: Spectral transmittance of IR filter
 $IR(\lambda)$: Spectral transmittance of the red filter in the CFA
 $M(\lambda)$: Spectral transmittance of the micro-lenses
 $CFA_R(\lambda)$: Spectral transmittance of the red filter in the CFA



Reading Sensor Specification: ONSem NOI4SM6600A

Monochromatic sensor



ELECTRO OPTICAL SPECIFICATIONS

Parameter	Specification
FPN (local)	<0.20%, 2 LSB10 ←
PRNU (local)	<1.5%
Conversion Gain	43 $\mu\text{V}/\text{e}^-$
Output Signal Amplitude	0.6 V
Saturation Charge	21500 e^-
Sensitivity (peak)	411 $\text{V}\cdot\text{m}^2/\text{W}\cdot\text{s}$ 4.83 $\text{V}/\text{lux}\cdot\text{s}$
Sensitivity (visible)	328 $\text{V}\cdot\text{m}^2/\text{W}\cdot\text{s}$ 2.01 $\text{V}/\text{lux}\cdot\text{s}$
Peak QE * FF Peak Spectral Response	25% ← 0.13 A/W
Fill Factor	35%
Dark Current	3.37 mV/s ← 78 e^-/s
Dark Signal Non Uniformity	8.28 mV/s 191 e^-/s
Temporal Noise	24 RMS e^- ←
Signal/Noise Ratio	895:1 (40 dB)
Dynamic Range	59 dB
Spectral Sensitivity Range	400 - 1000 nm
Optical Cross Talk	15% 4%
Power Dissipation	225 mW

Reading Sensor Specification: ONsemi KAF-8300

A RGB sensor

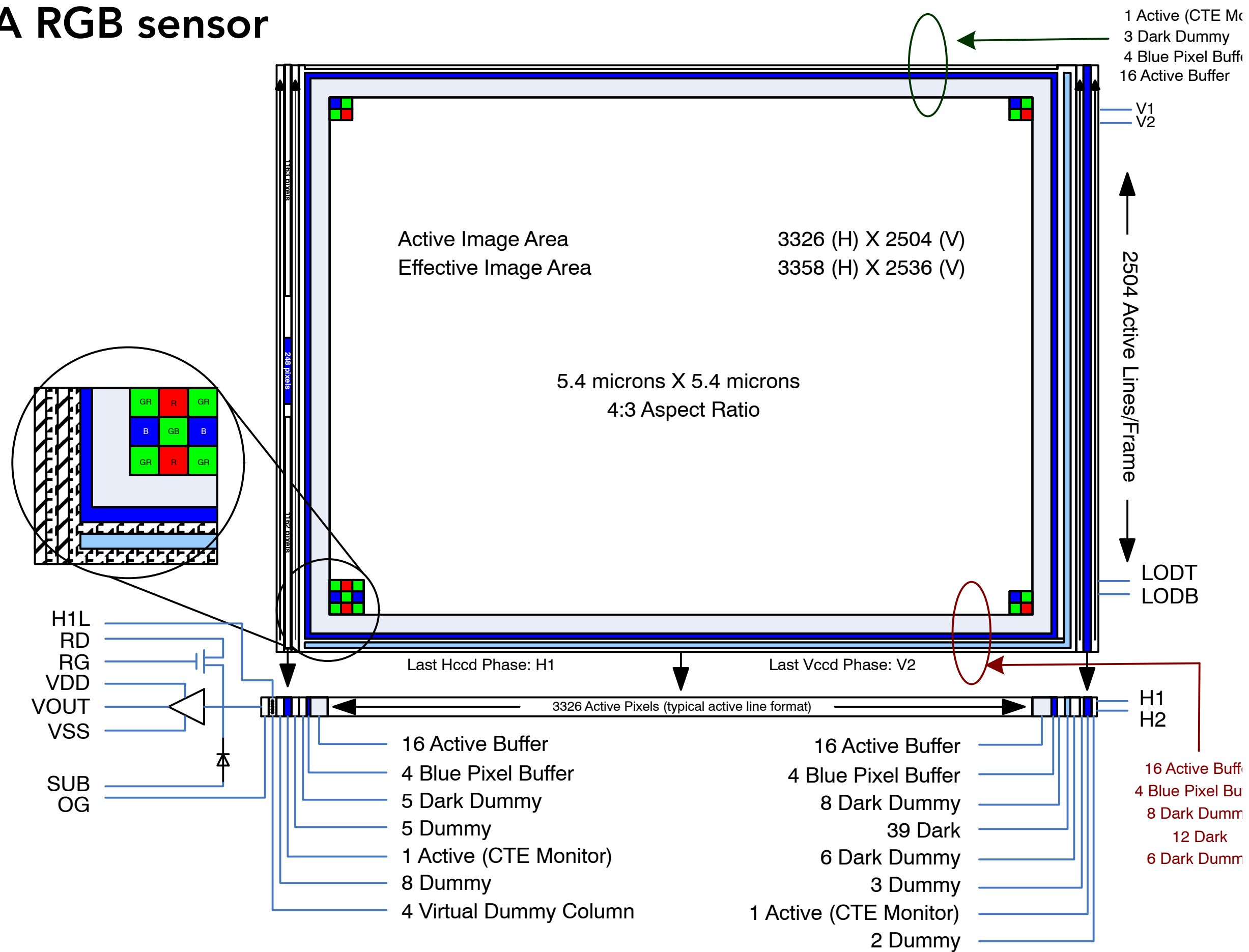


Figure 2. Block Diagram (Color)

Table 6. SPECIFICATIONS

Description	Symbol	Min.	Nom.	Max.	Unit
ALL DEVICES					
Minimum Column	MinColumn	575	-	-	mV
Linear Saturation Signal	N_{e^-SAT}	25.5	-	-	ke^-
Charge to Voltage Conversion	Q-V	22.5	23.0	-	$\mu V/e^-$
Linearity Error	LeLow10 LeLow33 LeHigh	-10 -10 -10	- - -	10 10 10	%
Dark Signal (Active Area Pixels)	AA_DarkSig	-	-	200	e^-/s
Dark Signal				200	e^-/s
Readout Rate				15	mV/s
Flush Current				90	mV/s
Dark Signal				3.0	mV p-p
	DSNU_Step DSNU_H	-	0.14 0.40	0.5 1.0	
Dark Signal Doubling Temperature	ΔT	-	5.8	-	$^{\circ}C$
Dark Reference Difference, Active Area	DarkStep	-3.5	0.15	3.5	mV
Total Noise	DfId_noi	-	-	1.08	mV
Total Sensor Noise	N	-	16	-	$e^- rms$
Linear Dynamic Range	DR	-	64.4	-	dB
Horizontal Charge Transfer Efficiency	HCTE	0.999990	0.999995	-	%
Vertical Charge Transfer Efficiency	VCTE	0.999997	0.999999	-	%
Blooming Protection	X_b	1,000	-	-	$\times E_{SAT}$
Vertical Bloom on Transfer	VBloomF	-20	-	20	mV
Horizontal Crosstalk	H_Xtalk	-20	-	20	mV
Horizontal Overclock Noise	Hoclk_noi	0	-	1.08	mV
Output Amplifier Bandwidth	f_{-3dB}	88	-	159	MHz
Output Impedance, Amplifier	R_{OUT}	100	-	180	Ω
Hclk Feedthru	V_{HFT}	-	-	70	mV
Reset Feedthru	V_{RFT}	500	710	1,000	mV

Dark current halves as the temperature drops by 5.8 $^{\circ}C$.

Reading Sensor Specification: ONsemi KAF-8300

The two green filters have slightly different spectral sensitivities!

Having microlenses improves spectral sensitivities because the FF improves!

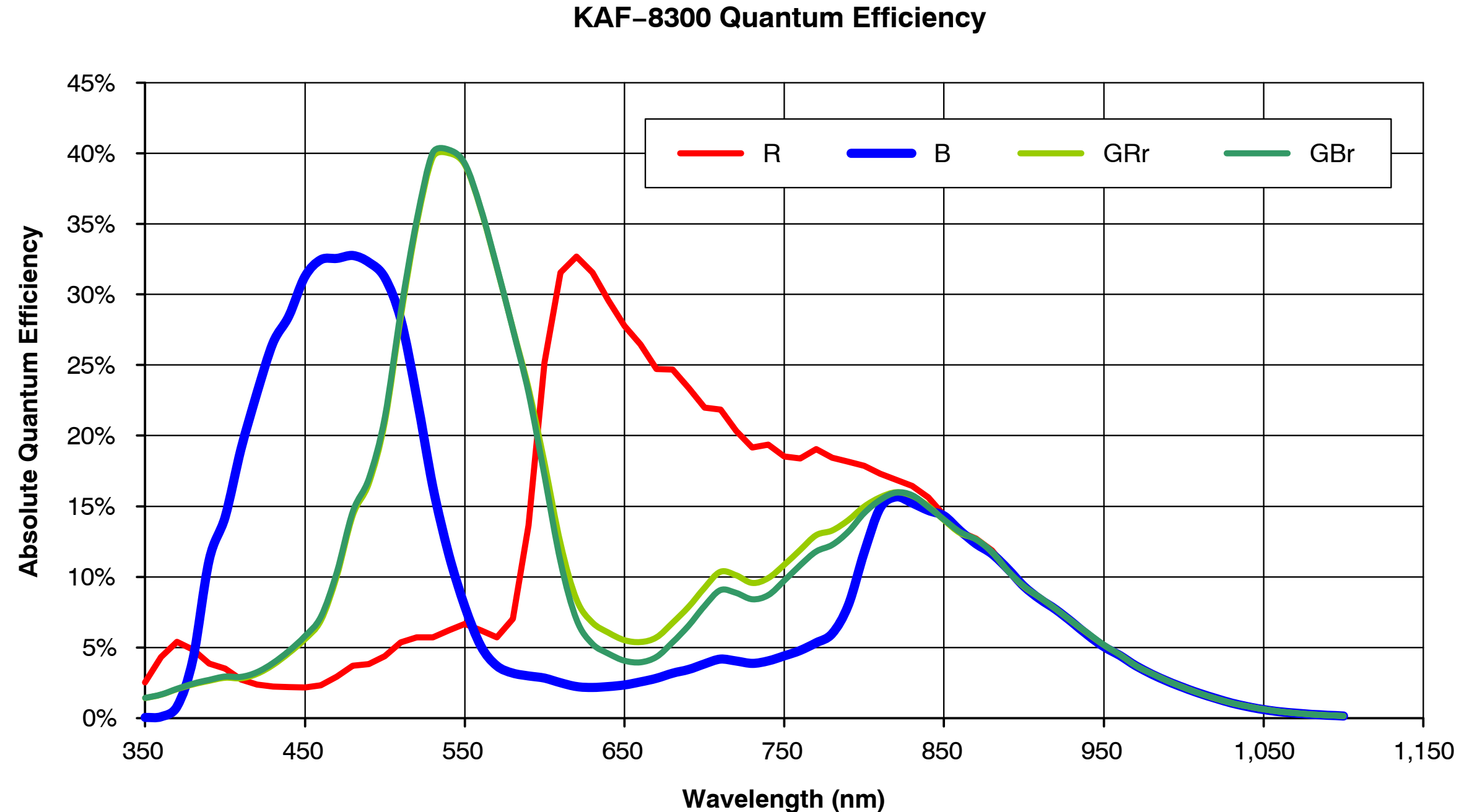


Figure 7. Typical Quantum Efficiency (Color Version)

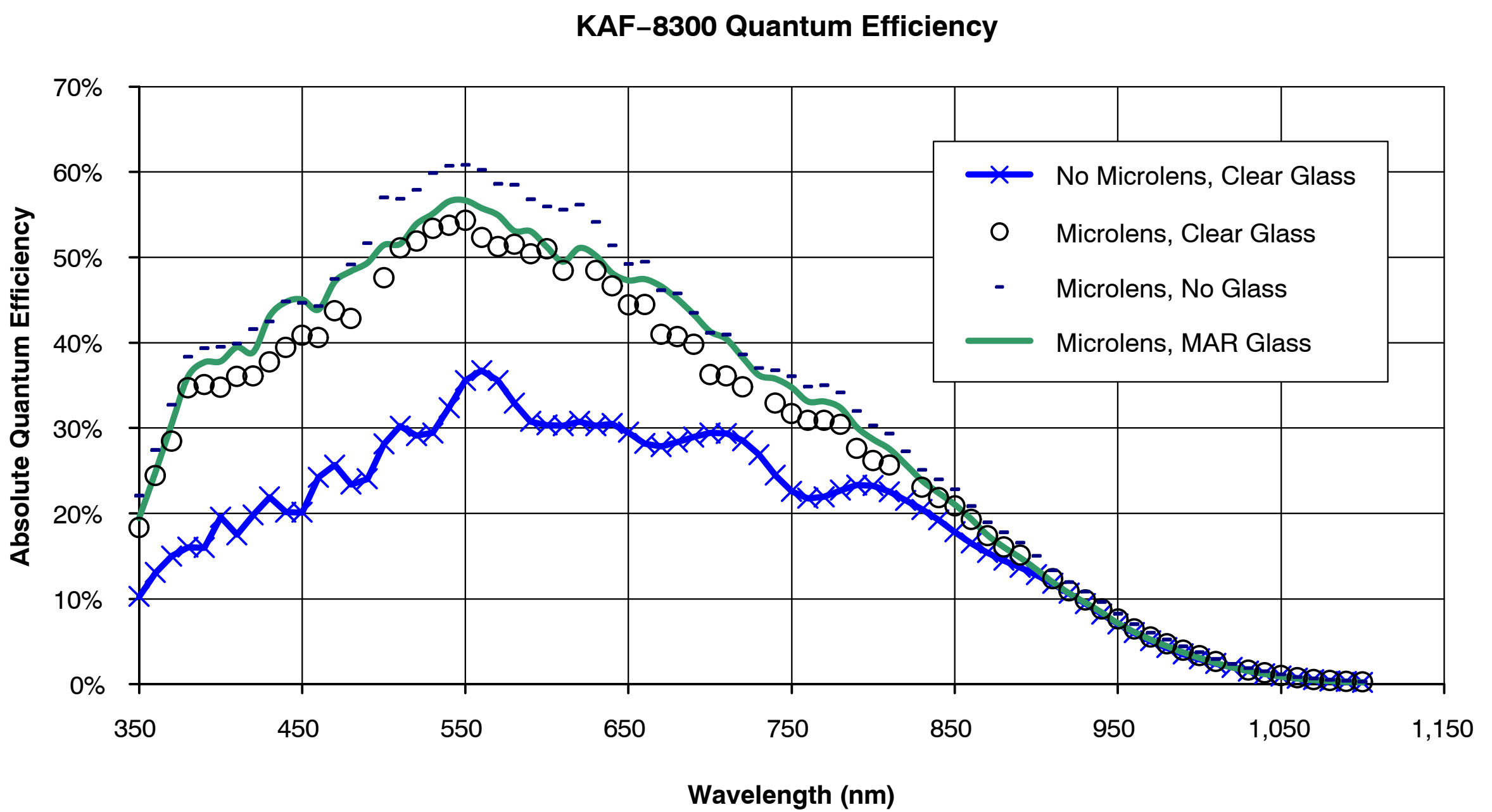
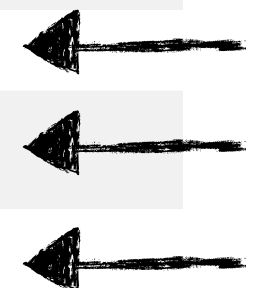


Figure 8. Typical Quantum Efficiency (All Monochrome Versions)

Reading Sensor Specification: Teledyne Prime-95B

Being a scientific image sensor, the noise performance is much better

Specifications	Camera Performance
Sensor	GPixel GSense 144 BSI CMOS Gen IV, Grade 1 in imaging area
Active Array Size	1200 x 1200 pixels (1.44 Megapixel)
Pixel Area	11µm x 11µm (121µm ²)
Sensor Area	13.2mm x 13.2mm 18.7mm diagonal
Peak QE%	>95%
Read Noise	1.6e- (Median) 1.8e- (RMS)
Full-Well Capacity	80,000e- (Combined Gain) 10,000e- (High Gain)
Dynamic Range	50,000:1 (Combined Gain)
Bit Depth	16-bit (Combined Gain) 12-bit (High Gain)
Readout Mode	Rolling Shutter Effective Global Shutter
Binning	2x2 (on FPGA)
Linearity	>99.5%



Cooling Performance	Sensor Temperature	Dark Current
Air Cooled	-20°C @ 25°C Ambient	0.55e-/pixel/second
Liquid Cooled	-25°C @ 25°C Ambient	0.3e-/pixel/second

