6.003: Signals and Systems

Modulation

December 6, 2011

Subject Evaluations

Your feedback is important to us!

Please give feedback to the staff and future 6.003 students:

http://web.mit.edu/subjectevaluation

Evaluations are open until Friday, December 16, at noon.

You will be able to view quantitative results at

http://web.mit.edu/subjectevaluation/results.html

and student-written summaries at

http://hkn.mit.edu/ug_sel.php

Communications Systems

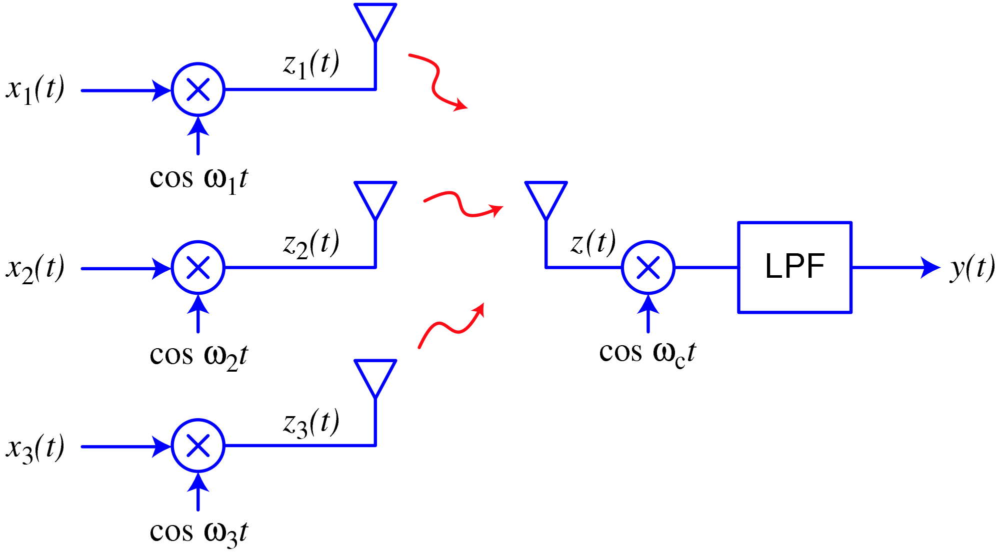
Signals are not always well matched to the media through which we wish to transmit them.

signal	applications
audio	telephone, radio, phonograph, CD, cell phone, MP3
video	television, cinema, HDTV, DVD
internet	coax, twisted pair, cable TV, DSL, optical fiber, E/M

Modulation can improve match based on **frequency**.

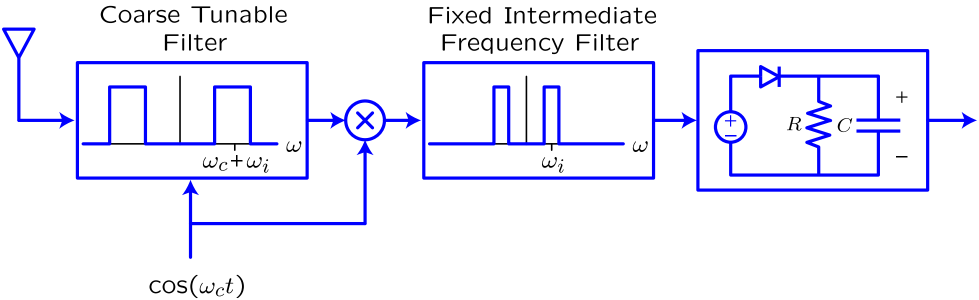
Amplitude Modulation

Amplitude modulation can be used to match audio frequencies to radio frequencies. It allows parallel transmission of multiple channels.



Superheterodyne Receiver

Edwin Howard Armstrong invented the superheterodyne receiver, which made broadcast AM practical.



Edwin Howard Armstrong also invented and patented the "regenerative" (positive feedback) circuit for amplifying radio signals (while he was a junior at Columbia University). He also invented wide-band FM.

Amplitude, Phase, and Frequency Modulation

There are many ways to embed a "message" in a carrier.

Amplitude Modulation (AM) + carrier: $y_1(t) = \big(x(t) + C\big)\cos(\omega_c t)$

Phase Modulation (PM): $y_2(t) = \cos(\omega_c t + kx(t))$

Frequency Modulation (FM): $y_3(t) = \cos\left(\omega_c t + k\int_{-\infty}^{t} x(\tau)d\tau\right)$

PM: signal modulates instantaneous phase of the carrier.

$$y_2(t) = \cos(\omega_c t + kx(t))$$

FM: signal modulates instantaneous frequency of carrier.

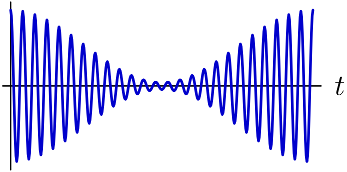
$$y_3(t) = \cos\left(\omega_c t + \underbrace{k\int_{-\infty}^{t} x(\tau)d\tau}_{\phi(t)}\right)$$

$$\omega_i(t) = \omega_c + \frac{d}{dt}\phi(t) = \omega_c + kx(t)$$

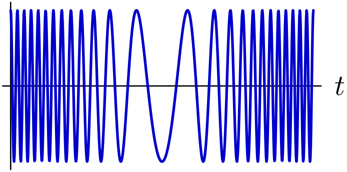
Frequency Modulation

Compare AM to FM for $x(t) = \cos(\omega_m t)$.

AM: $y_1(t) = \big(x(t) + C\big)\cos(\omega_c t) = (\cos(\omega_m t) + 1.1)\cos(\omega_c t)$



FM: $y_3(t) = \cos\left(\omega_c t + k\int_{-\infty}^{t} x(\tau)d\tau\right) = \cos(\omega_c t + \frac{k}{\omega_m}\sin(\omega_m t))$



Advantages of FM:

- constant power
- no need to transmit carrier (unless DC important)
- bandwidth?

Frequency Modulation

Early investigators thought that narrowband FM could have arbitrarily narrow bandwidth, allowing more channels than AM.

$$y_3(t) = \cos\left(\omega_c t + \underbrace{k\int_{-\infty}^{t} x(\tau)d\tau}_{\phi(t)}\right)$$

$$\omega_i(t) = \omega_c + \frac{d}{dt}\phi(t) = \omega_c + kx(t)$$

Small $k \rightarrow$ small bandwidth. Right?

Frequency Modulation

Early investigators thought that narrowband FM could have arbitrarily narrow bandwidth, allowing more channels than AM. **Wrong!**

$$
\begin{aligned}
y_3(t) &= \cos\left(\omega_c t + k\int_{-\infty}^{t} x(\tau)d\tau\right) \\
&= \cos(\omega_c t) \times \cos\left(k\int_{-\infty}^{t} x(\tau)d\tau\right) - \sin(\omega_c t) \times \sin\left(k\int_{-\infty}^{t} x(\tau)d\tau\right)
\end{aligned}
$$

If $k \to 0$ then

$$\cos\left(k\int_{-\infty}^{t} x(\tau)d\tau\right) \to 1$$

$$\sin\left(k\int_{-\infty}^{t} x(\tau)d\tau\right) \to k\int_{-\infty}^{t} x(\tau)d\tau$$

$$y_3(t) \approx \cos(\omega_c t) - \sin(\omega_c t) \times \left(k\int_{-\infty}^{t} x(\tau)d\tau\right)$$

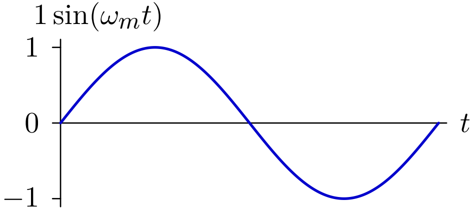
Bandwidth of narrowband FM is the same as that of AM!
(integration does not change the highest frequency in the signal)

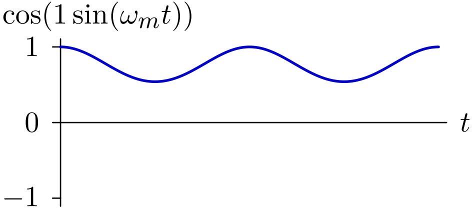
Phase/Frequency Modulation

Find the Fourier transform of a PM/FM signal.

$$y(t) = \cos(\omega_c t + m x(t)) = \cos(\omega_c t + m \sin(\omega_m t))$$
$$= \cos(\omega_c t) \cos(m \sin(\omega_m t)) - \sin(\omega_c t) \sin(m \sin(\omega_m t))$$

$x(t)$ is periodic in $T = \frac{2\pi}{\omega_m}$, therefore $\cos(m \sin(\omega_m t))$ is periodic in T.





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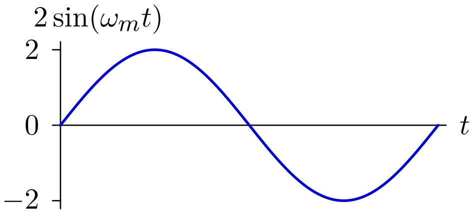

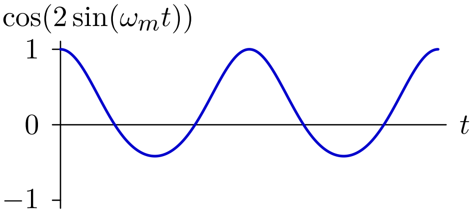

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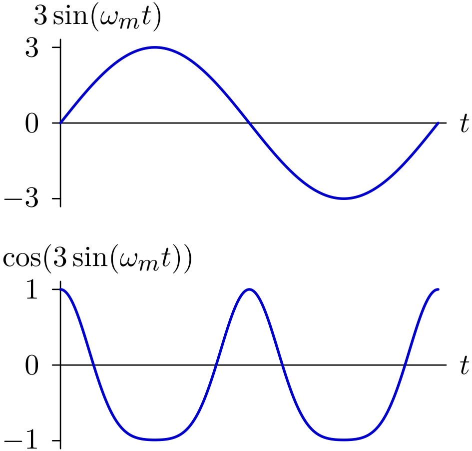

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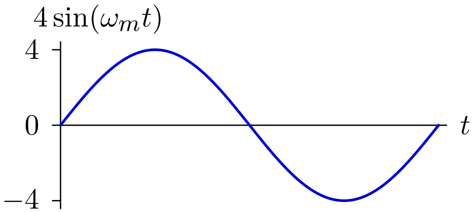

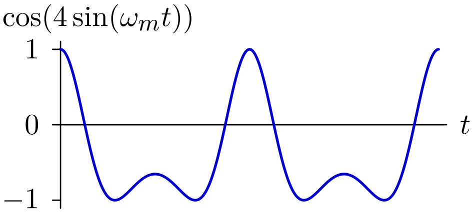

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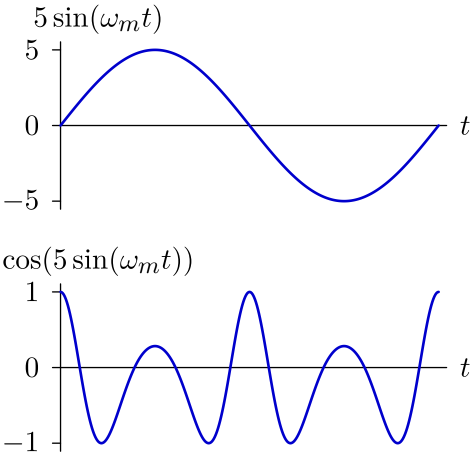

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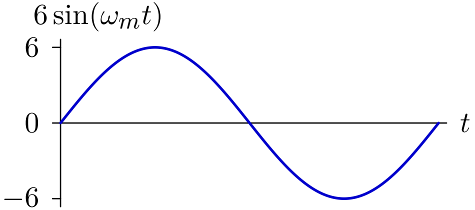

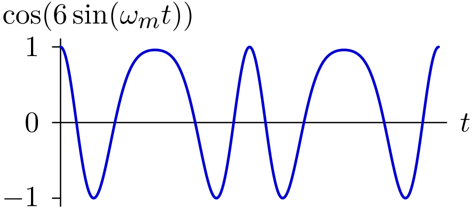

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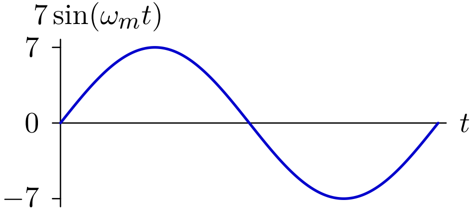

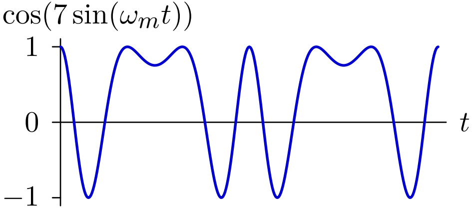

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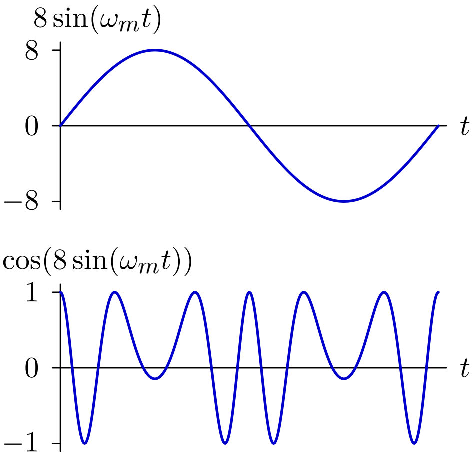

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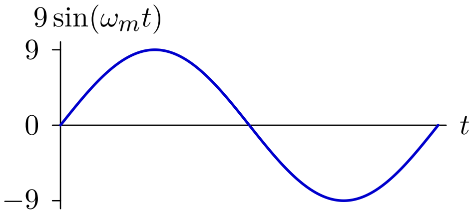

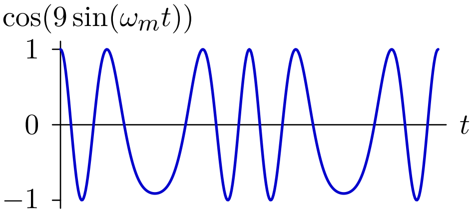

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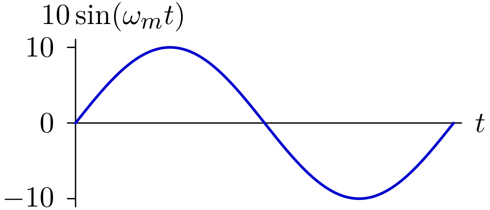

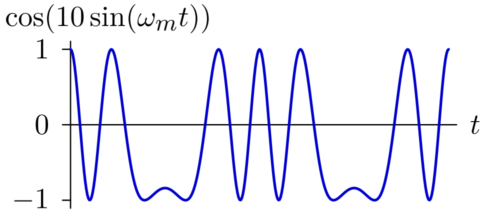

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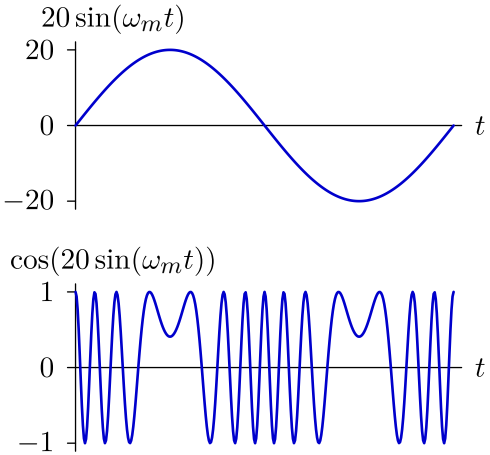

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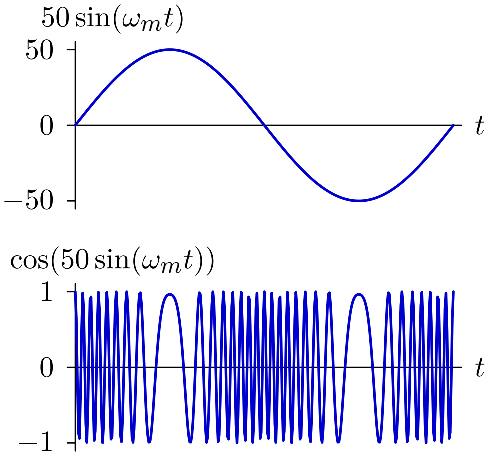

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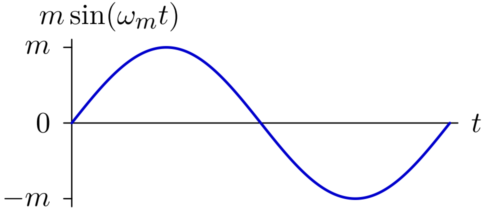

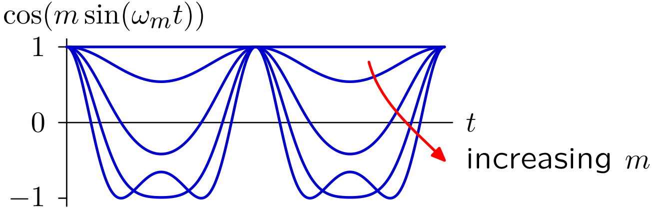

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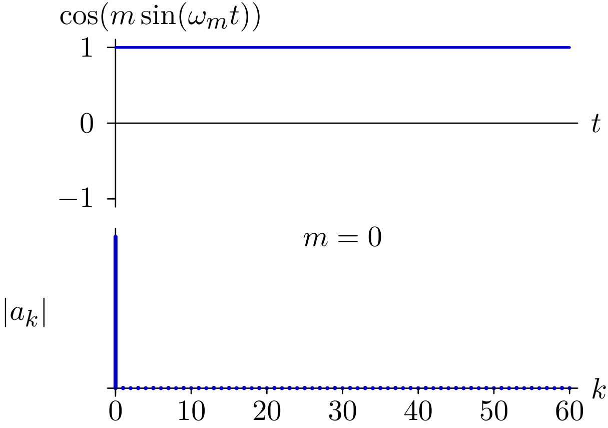

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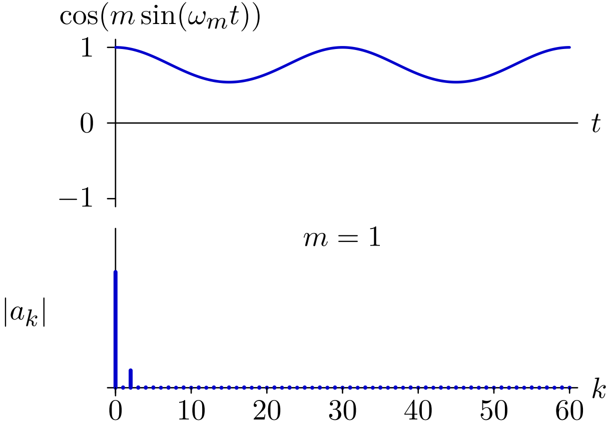

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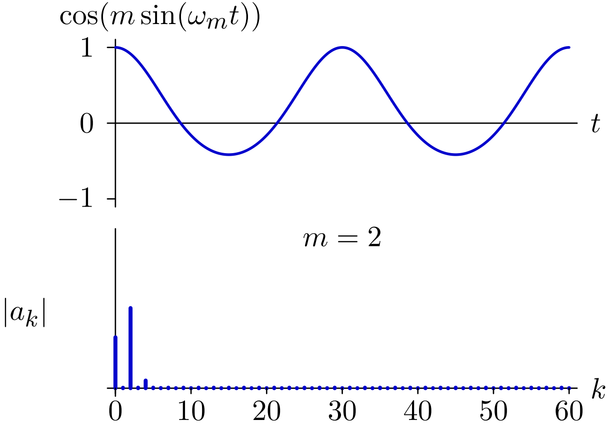

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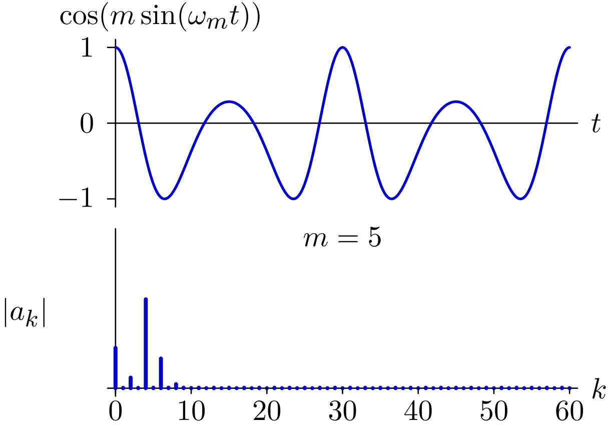

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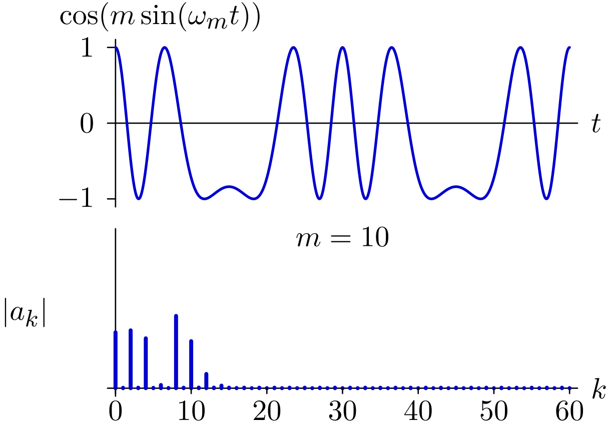

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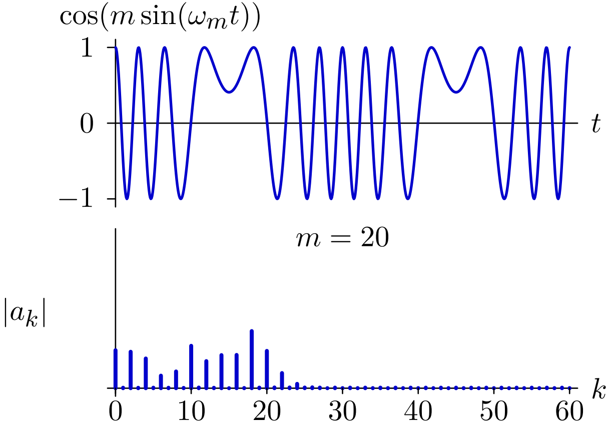

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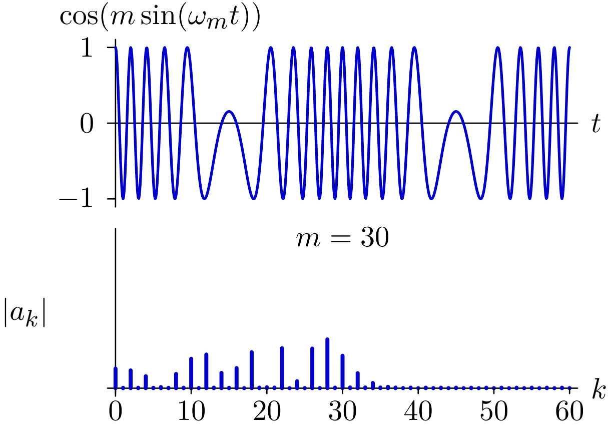

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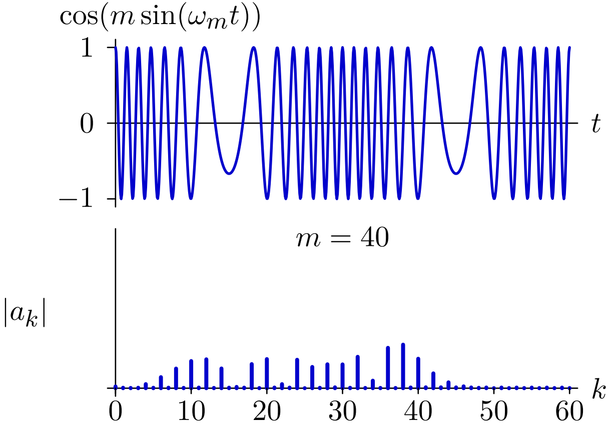

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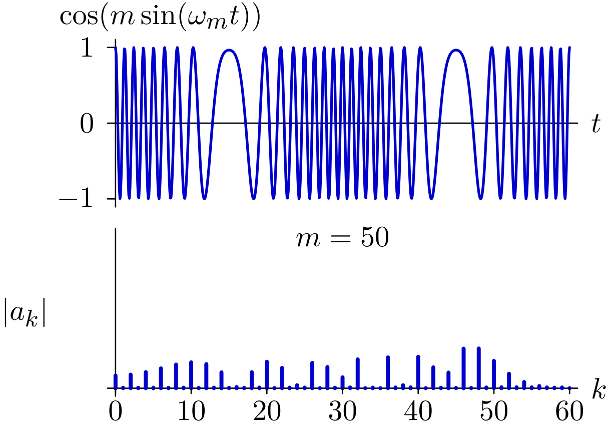


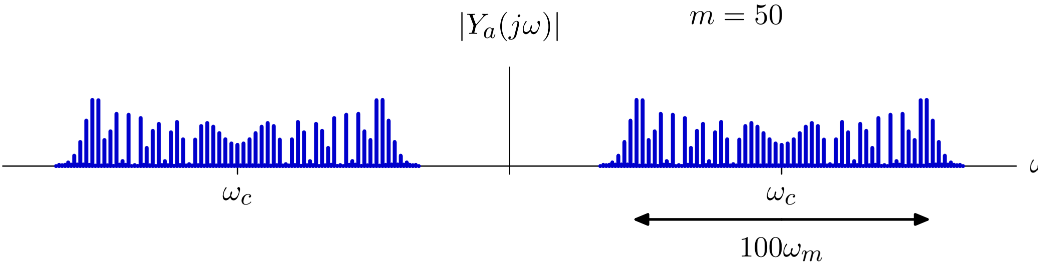
Phase/Frequency Modulation

Fourier transform of first part.

$$x(t) = \sin(\omega_m t)$$

$$y(t) = \cos(\omega_c t + m x(t)) = \cos(\omega_c t + m \sin(\omega_m t))$$

$$= \underbrace{\cos(\omega_c t)\cos(m \sin(\omega_m t))}_{y_a(t)} - \sin(\omega_c t)\sin(m \sin(\omega_m t))$$

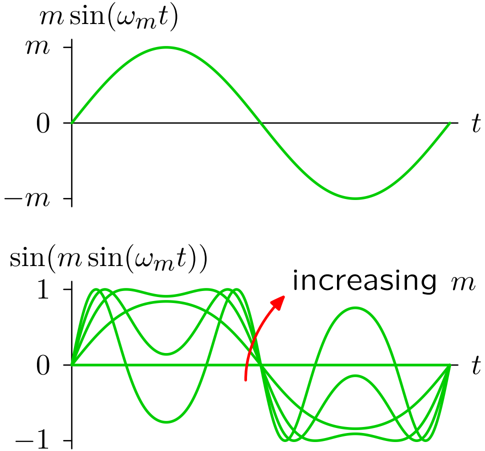


Phase/Frequency Modulation

Find the Fourier transform of a PM/FM signal.

$$y(t) = \cos(\omega_c t + m x(t)) = \cos(\omega_c t + m \sin(\omega_m t))$$
$$= \cos(\omega_c t)\cos(m \sin(\omega_m t)) - \sin(\omega_c t)\sin(m \sin(\omega_m t))$$

$x(t)$ is periodic in $T = \frac{2\pi}{\omega_m}$, therefore $\sin(m \sin(\omega_m t))$ is periodic in T.



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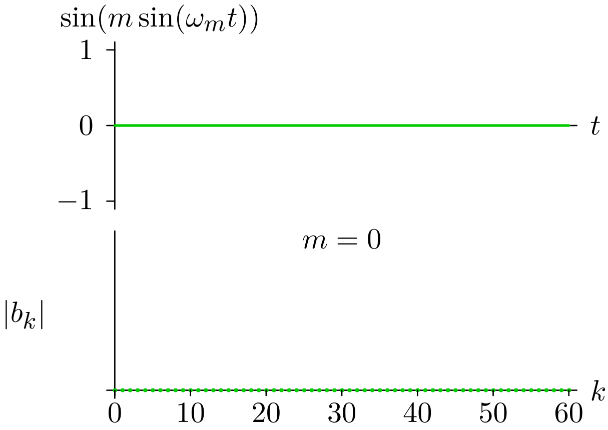

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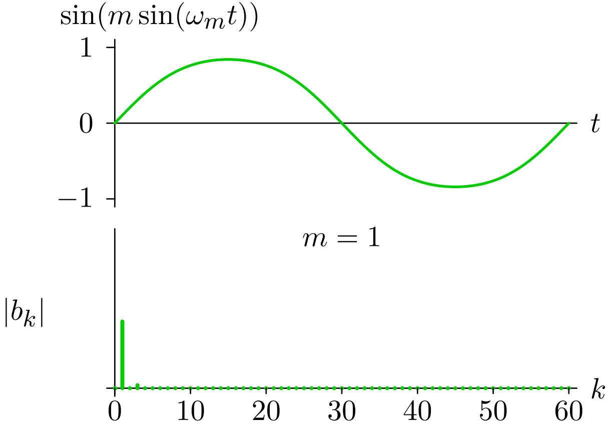

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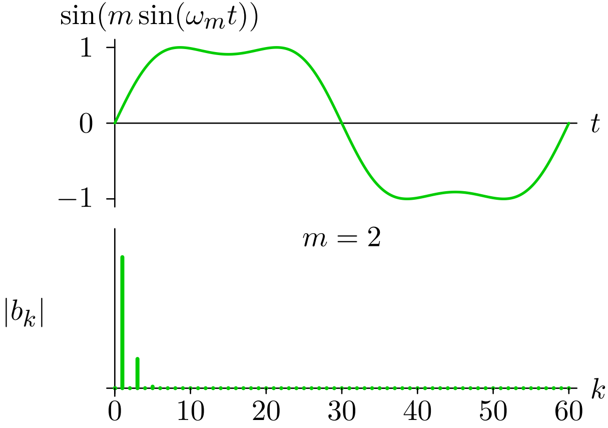

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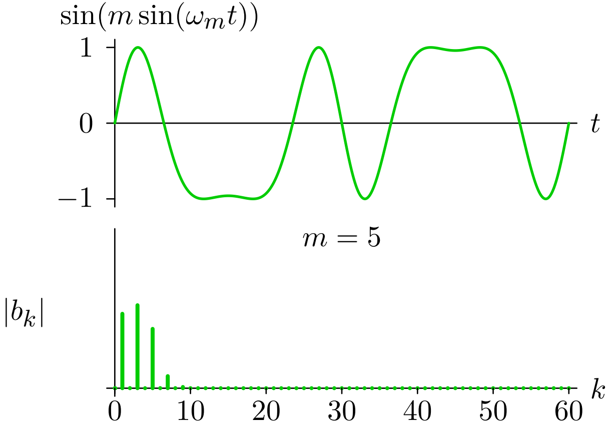

Phase/Frequency Modulation

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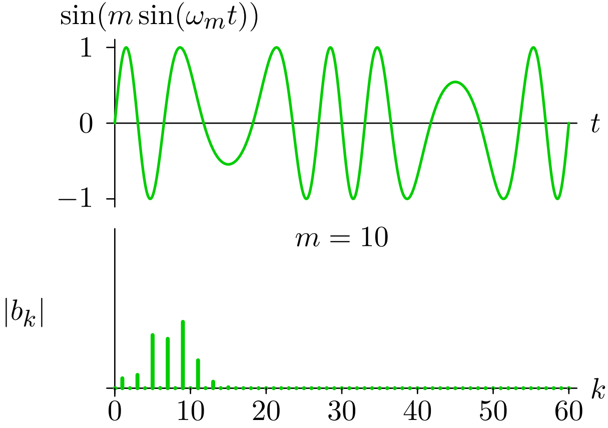

Phase/Frequency Modulation

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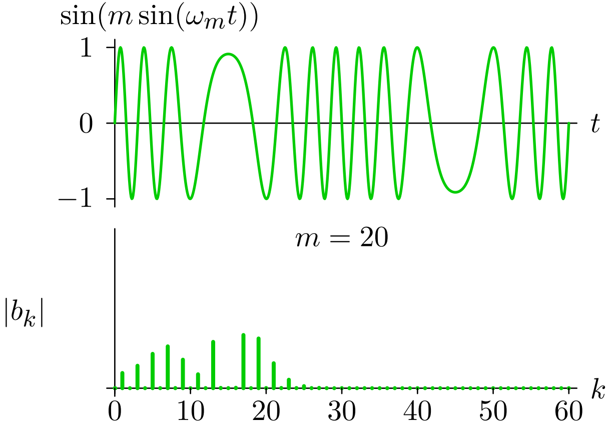

Phase/Frequency Modulation

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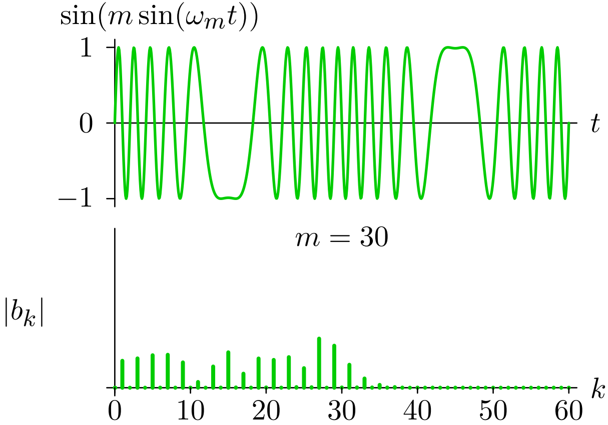

Phase/Frequency Modulation

Find the Fourier transform of a PM/FM signal.

$$y(t) = \cos(\omega_c t + m x(t)) = \cos(\omega_c t + m\sin(\omega_m t))$$
$$= \cos(\omega_c t)\cos(m\sin(\omega_m t)) - \sin(\omega_c t)\sin(m\sin(\omega_m t))$$

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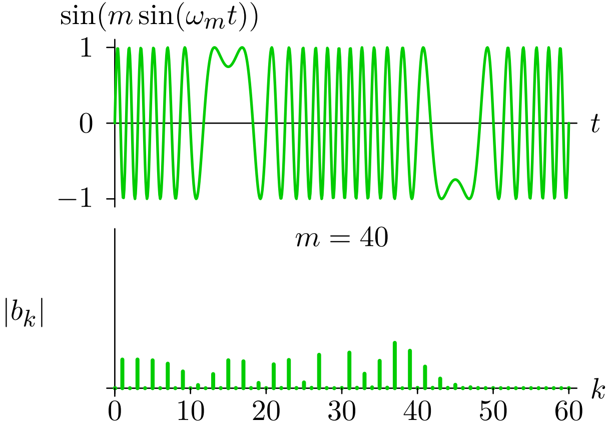

Phase/Frequency Modulation

Find the Fourier transform of a PM/FM signal.

$$y(t) = \cos(\omega_c t + mx(t)) = \cos(\omega_c t + m\sin(\omega_m t))$$

$$= \cos(\omega_c t)\cos(m\sin(\omega_m t)) - \sin(\omega_c t)\sin(m\sin(\omega_m t))$$

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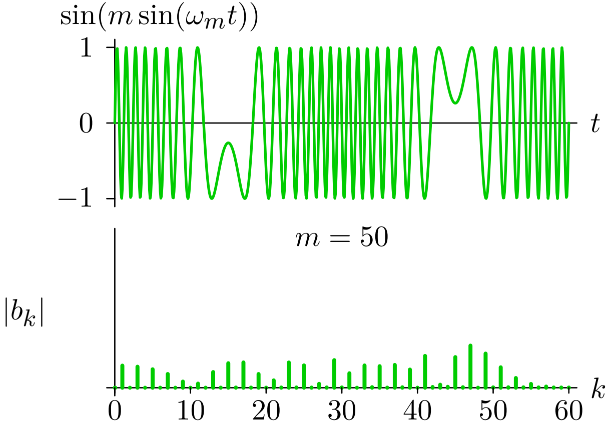


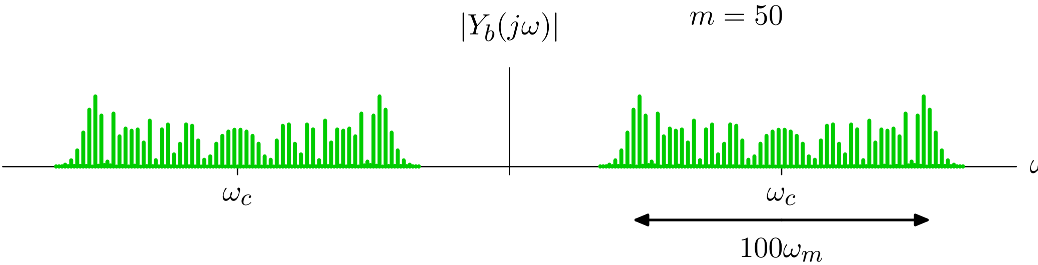
Phase/Frequency Modulation

Fourier transform of second part.

$$x(t) = \sin(\omega_m t)$$

$$y(t) = \cos(\omega_c t + m x(t)) = \cos(\omega_c t + m \sin(\omega_m t))$$

$$= \cos(\omega_c t)\cos(m \sin(\omega_m t)) - \underbrace{\sin(\omega_c t)\sin(m \sin(\omega_m t))}_{y_b(t)}$$



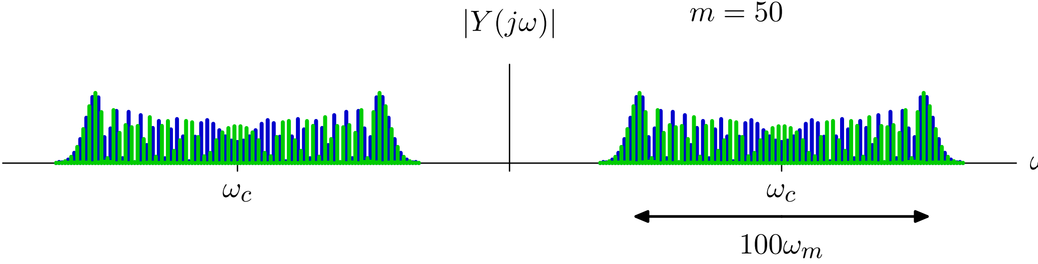
Phase/Frequency Modulation

Fourier transform.

$$x(t) = \sin(\omega_m t)$$

$$y(t) = \cos(\omega_c t + m x(t)) = \cos(\omega_c t + m \sin(\omega_m t))$$

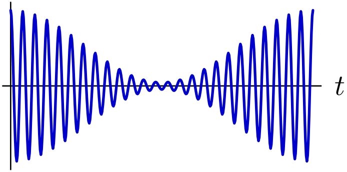
$$= \underbrace{\cos(\omega_c t)\cos(m\sin(\omega_m t))}_{y_a(t)} - \underbrace{\sin(\omega_c t)\sin(m\sin(\omega_m t))}_{y_b(t)}$$



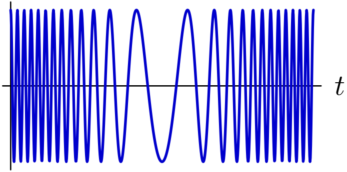
Frequency Modulation

Wideband FM is useful because it is robust to noise.

AM: $y_1(t) = (\cos(\omega_m t) + 1.1)\cos(\omega_c t)$



FM: $y_3(t) = \cos(\omega_c t + m\sin(\omega_m t))$



FM generates a redundant signal that is resilient to additive noise.

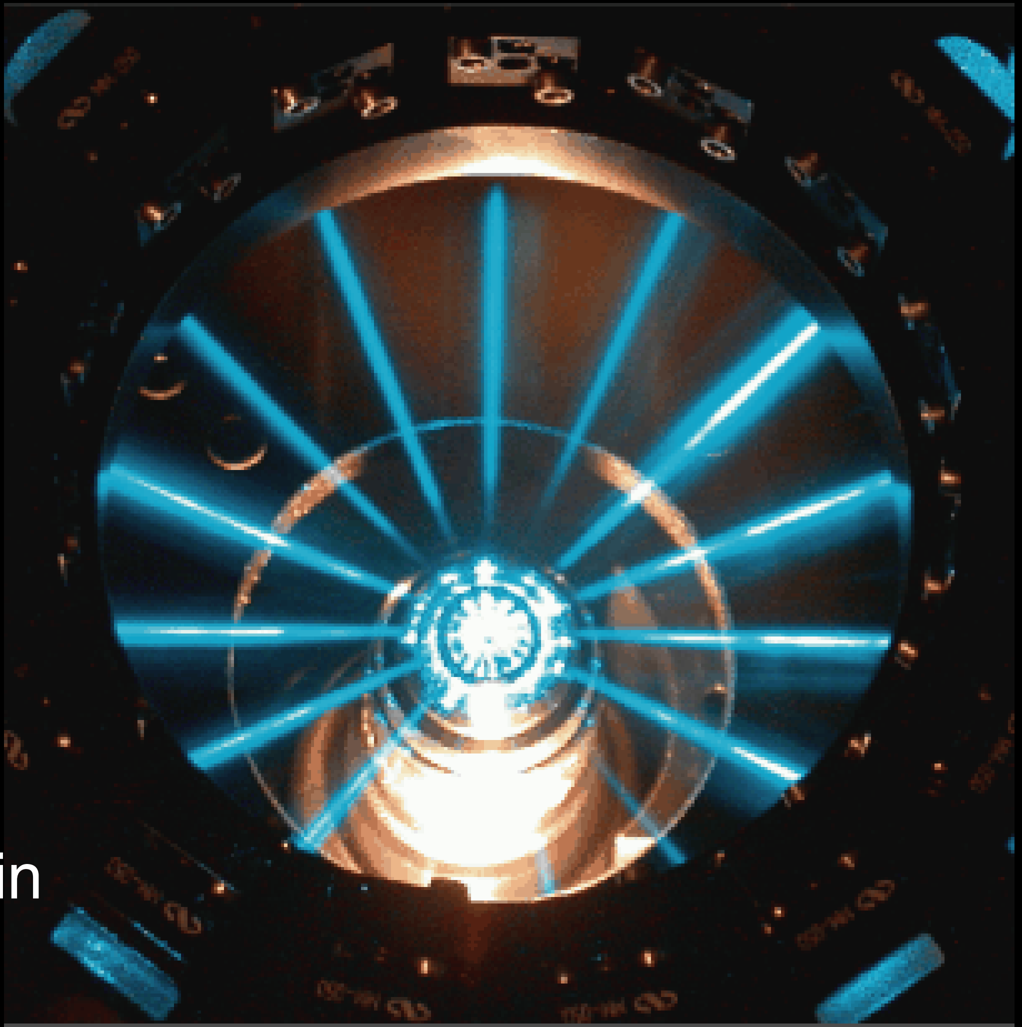
Summary

Modulation is useful for matching signals to media.

Examples: commercial radio (AM and FM)

Close with unconventional application of modulation – in microscopy.

6.003 Microscopy

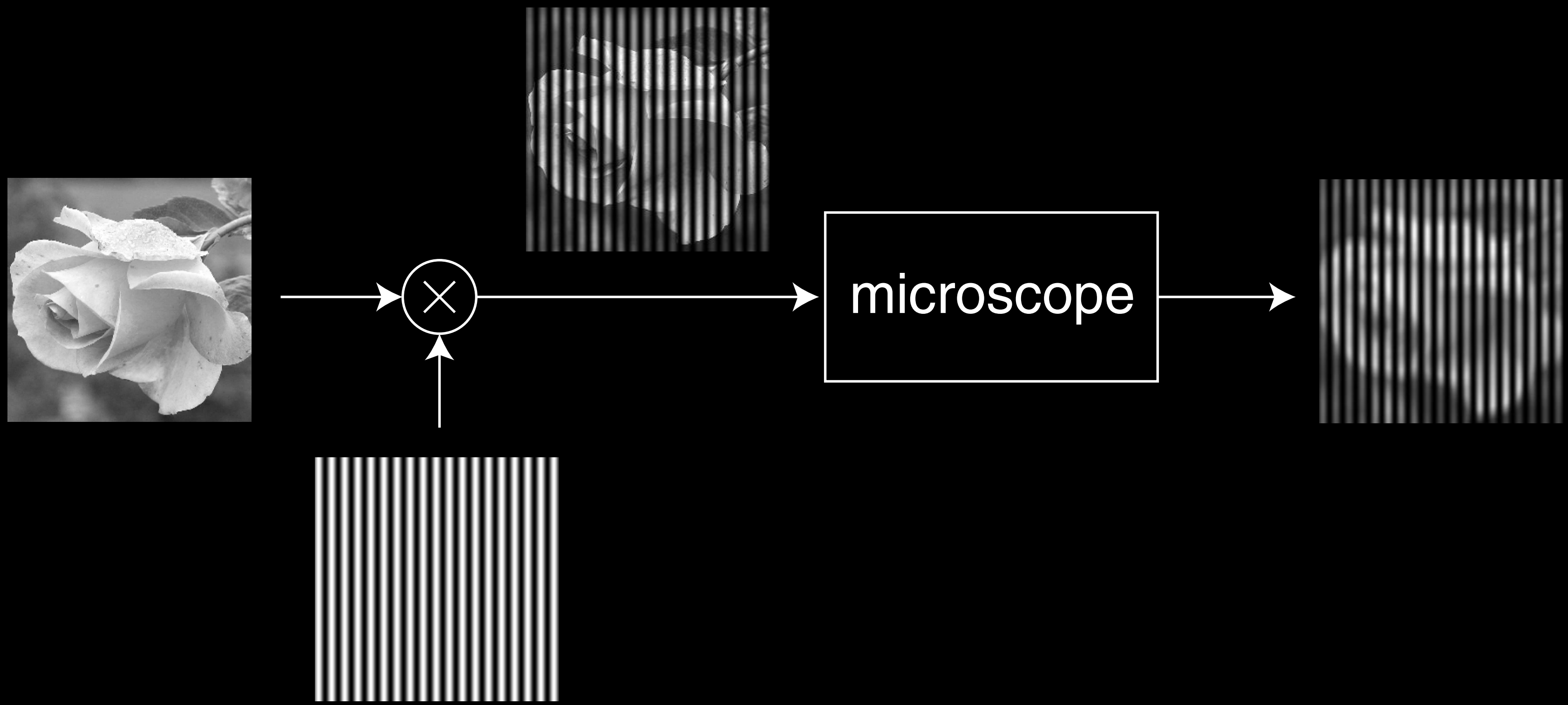


Dennis M. Freeman
Stanley S. Hong
Jekwan Ryu
Michael S. Mermelstein
Berthold K. P. Horn

6.003 Model of a Microscope

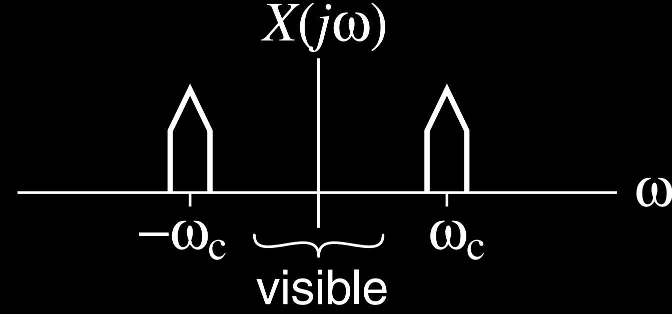
Microscope = low-pass filter

Phase-Modulated Microscopy

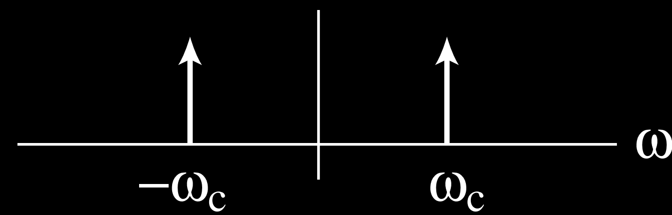


Phase-Modulated Microscopy

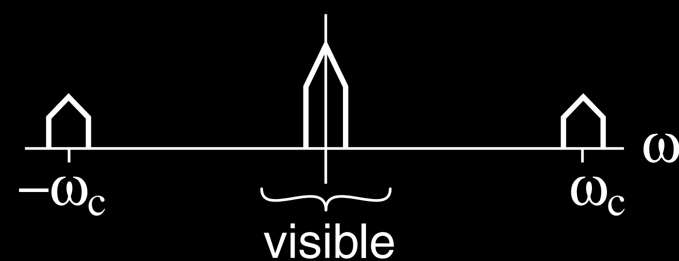
Poster: $\cos(\omega_c y + f(x,y))$



Projector: $\cos(\omega_c y)$

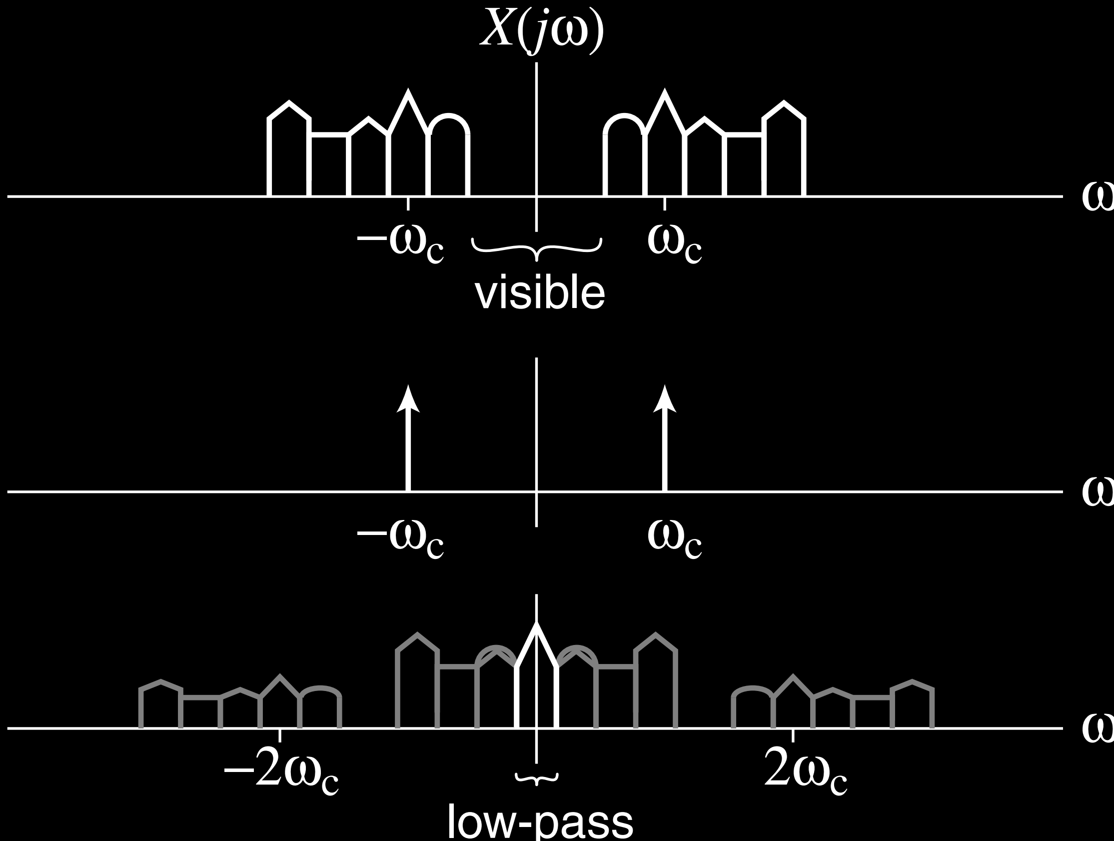


Poster with Projector: $\cos(\omega_c y)\,\cos(\omega_c y + f(x,y))$



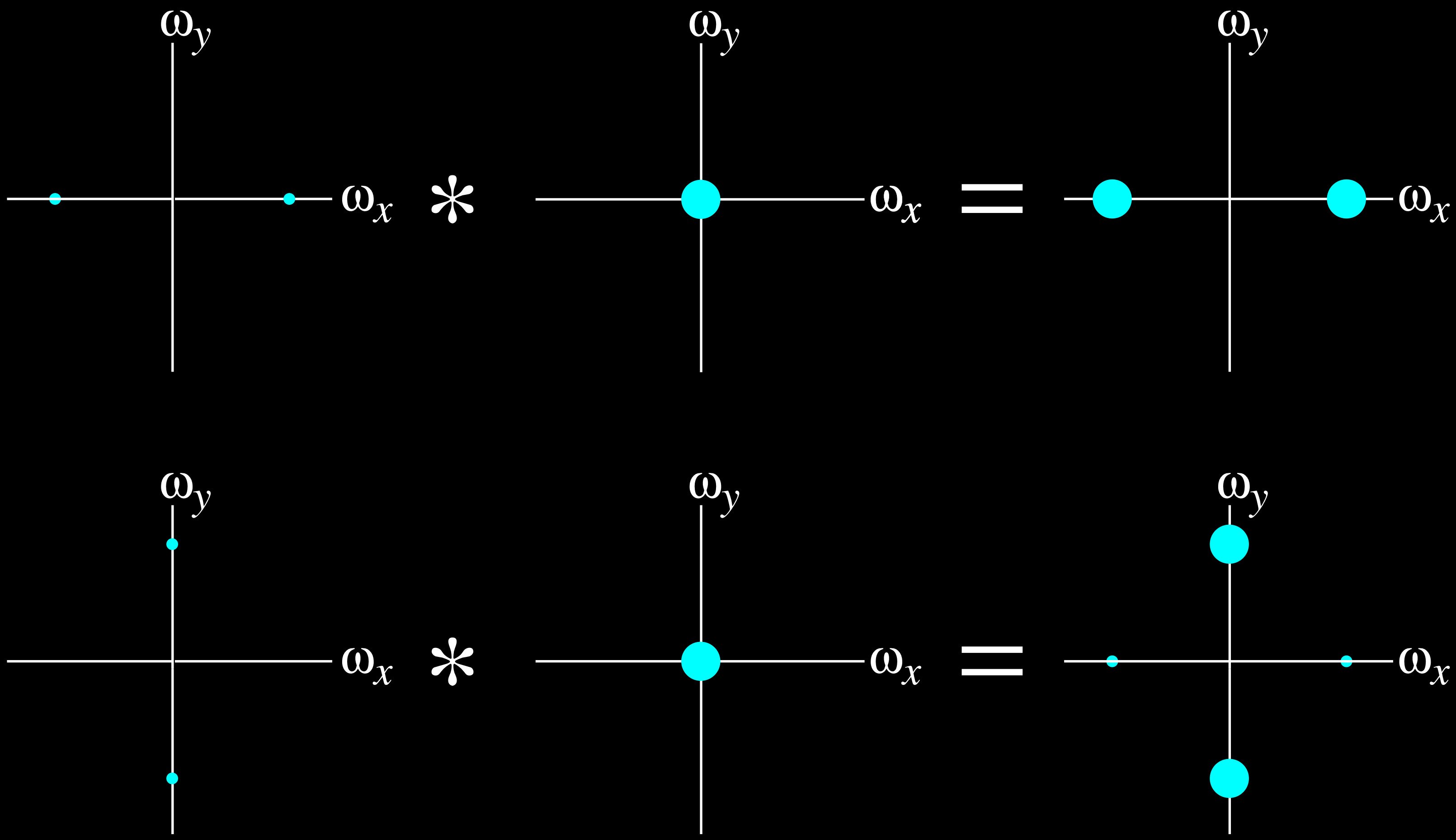
Modulated illumination enables low-pass system (eyes) to detect high spatial frequencies

Phase-Modulated Microscopy

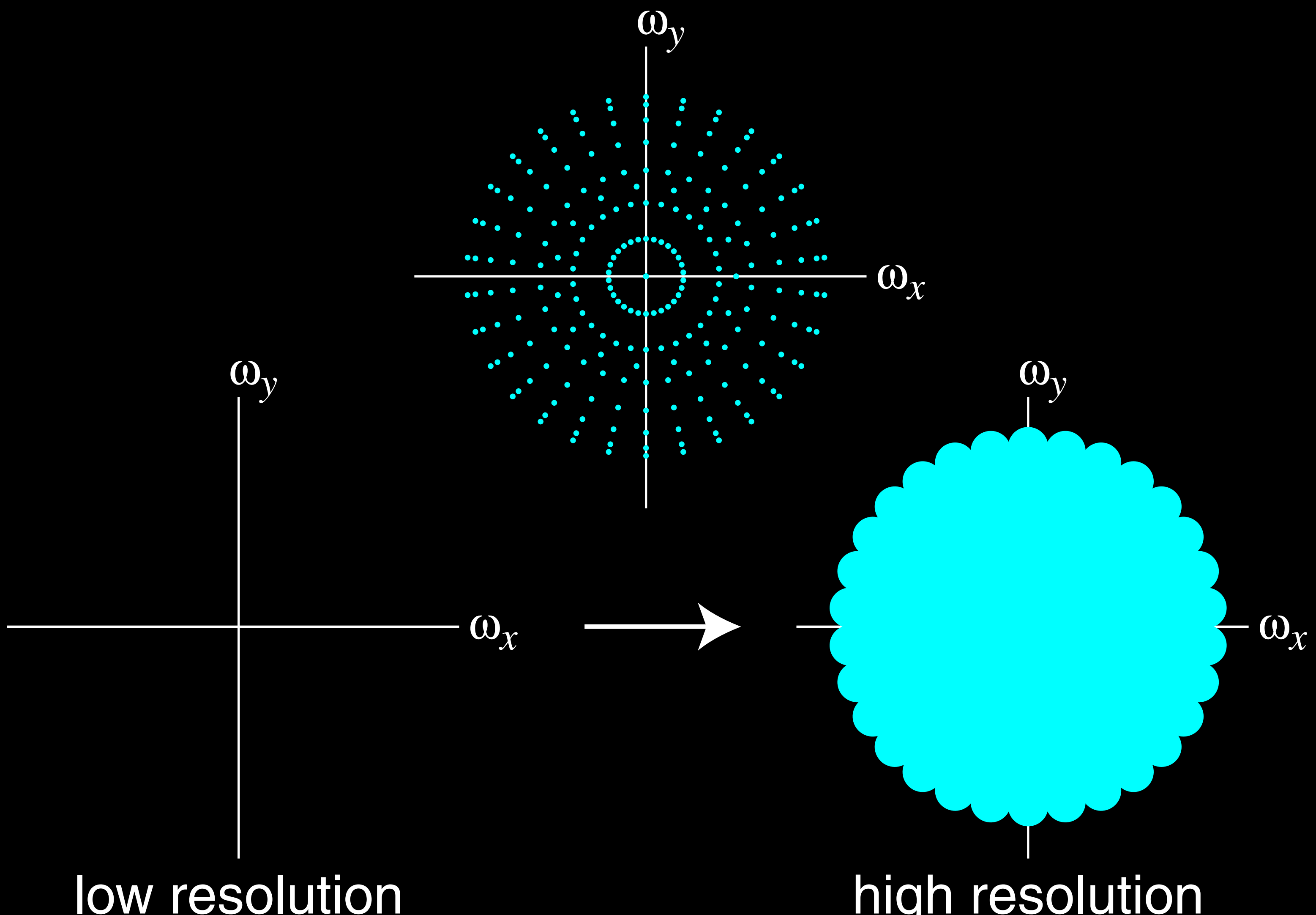


Modulated illumination enables low-pass system (eyes) to detect high spatial frequencies

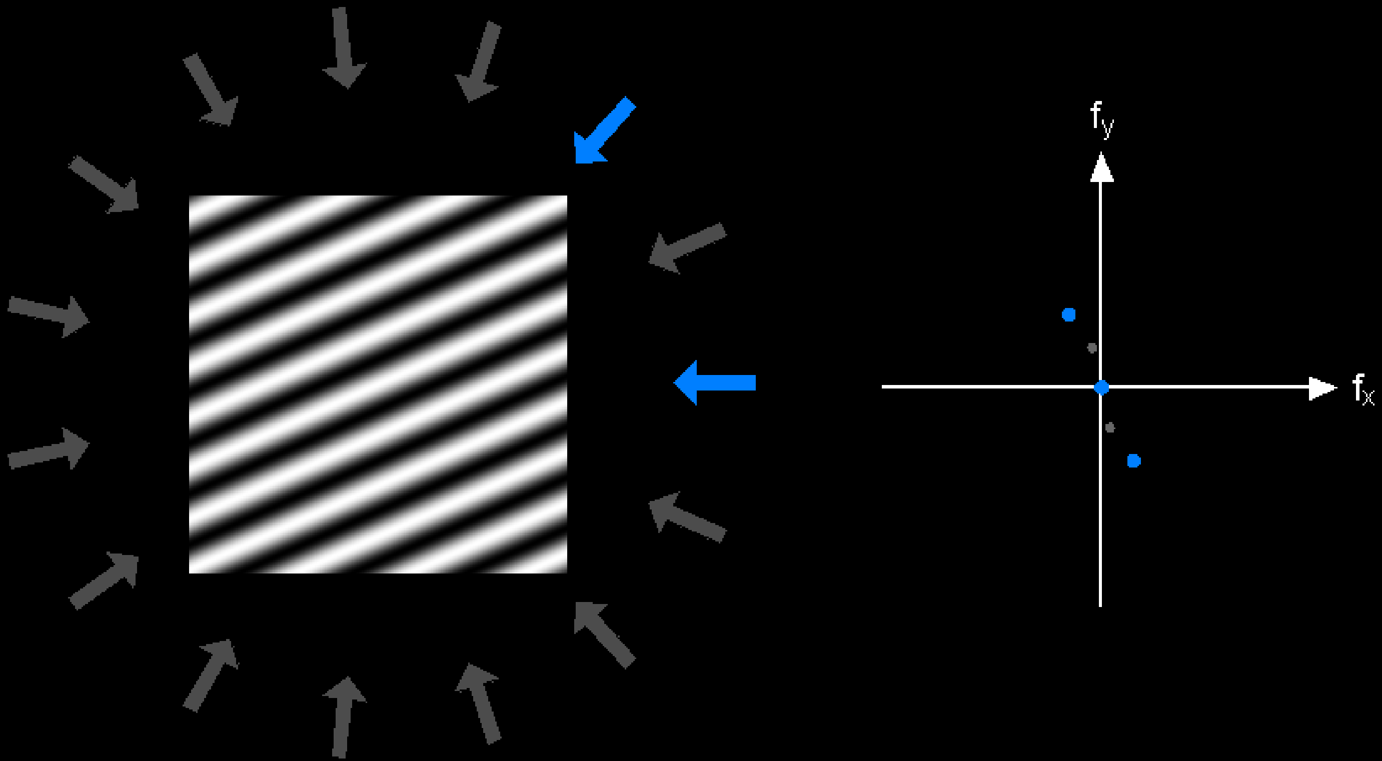
Images are 2 dimensional
→ need 2D Fourier Transform



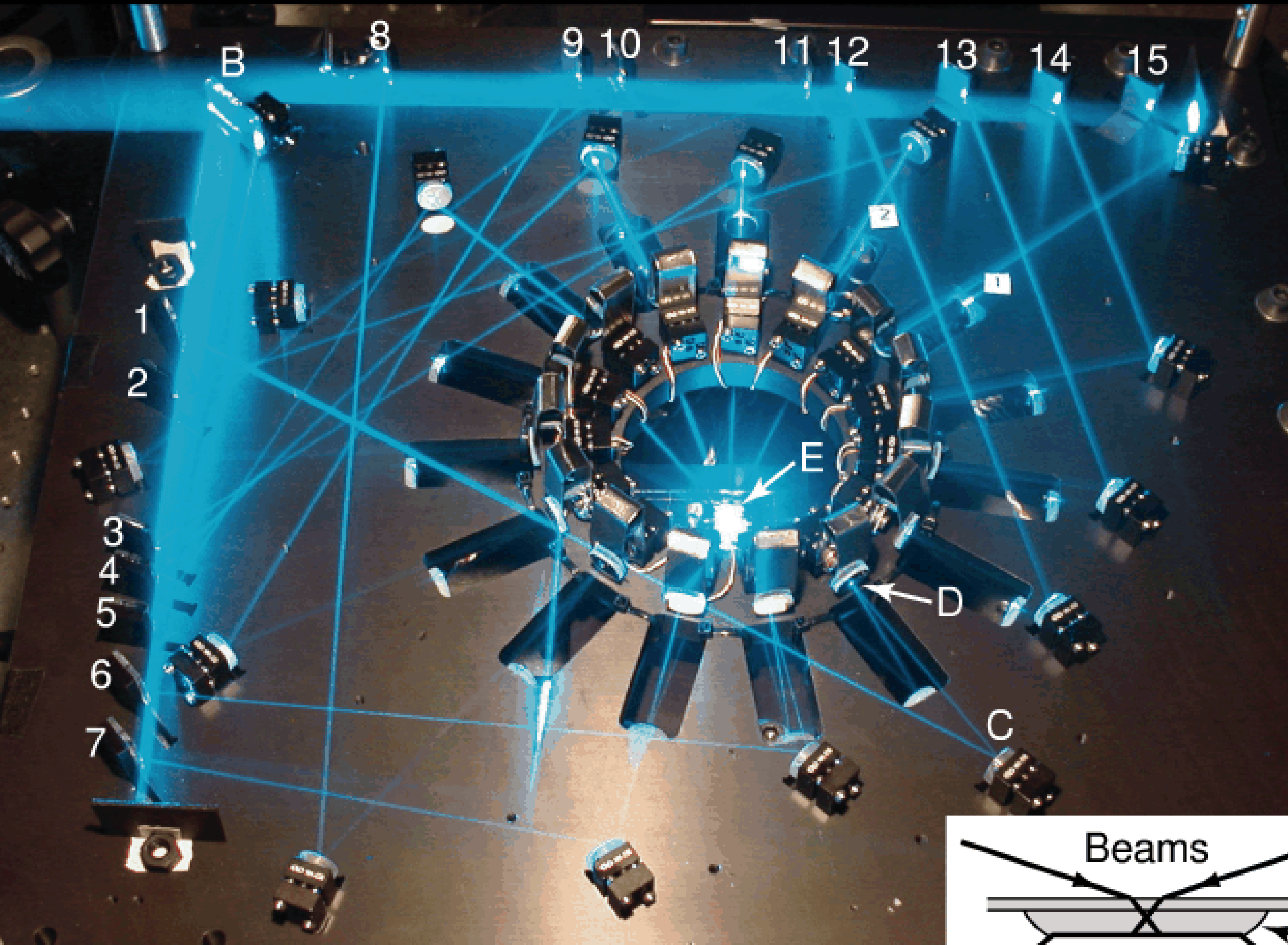
many frequencies + many orientations = many images



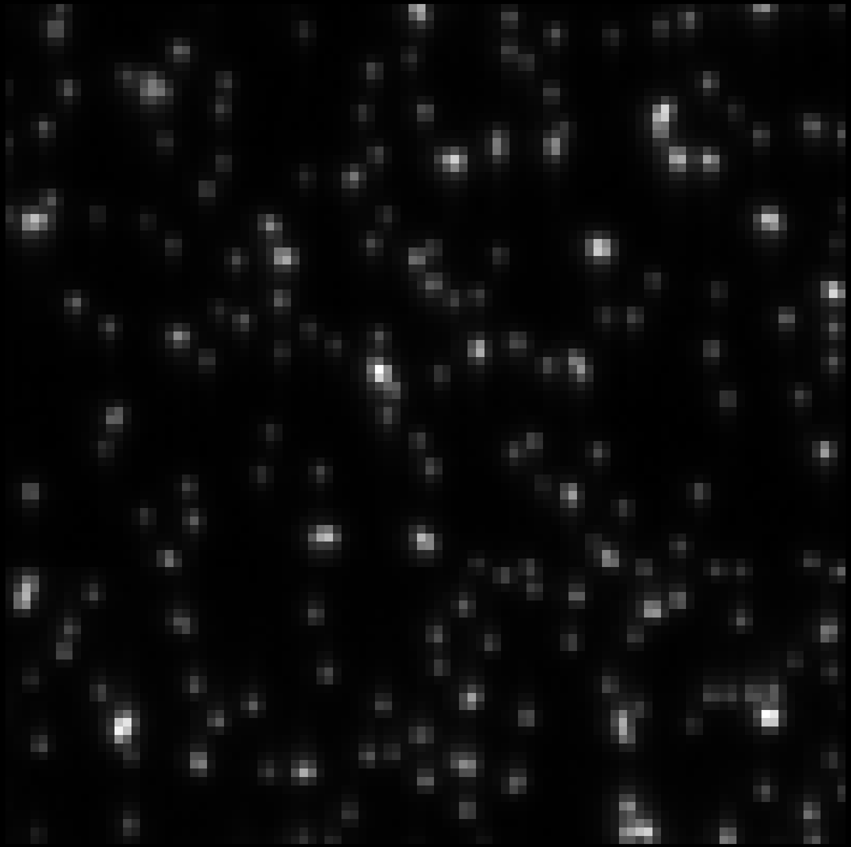
Standing-wave illumination spectrum



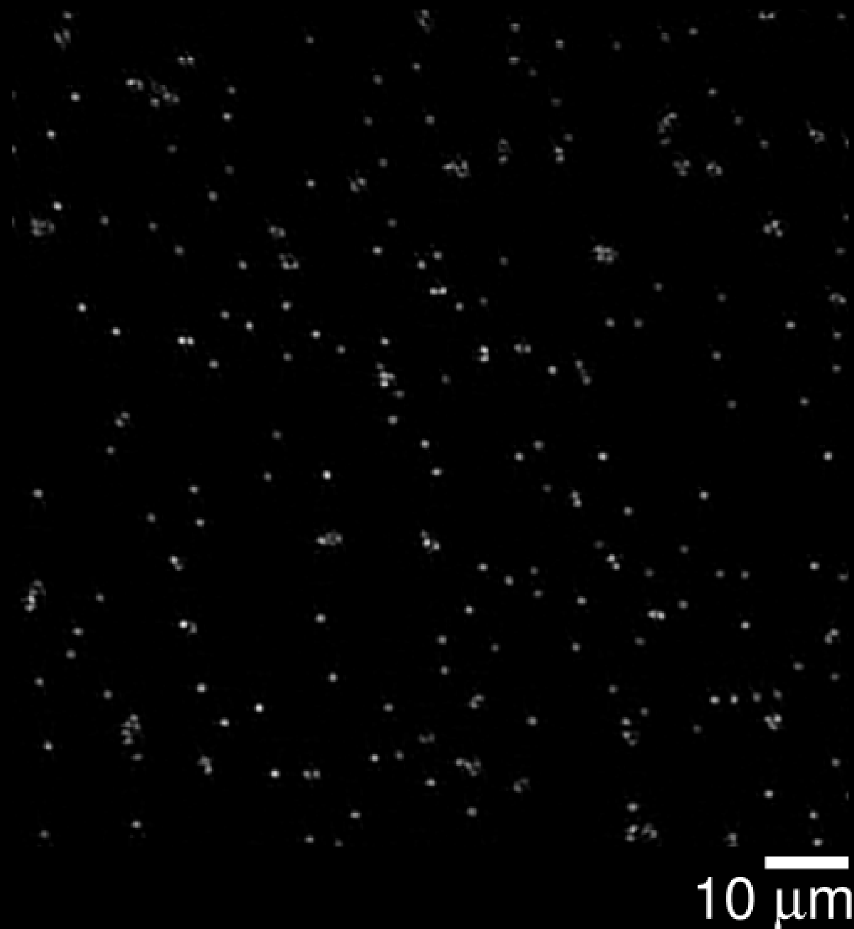
Thanks to M. Mermelstein

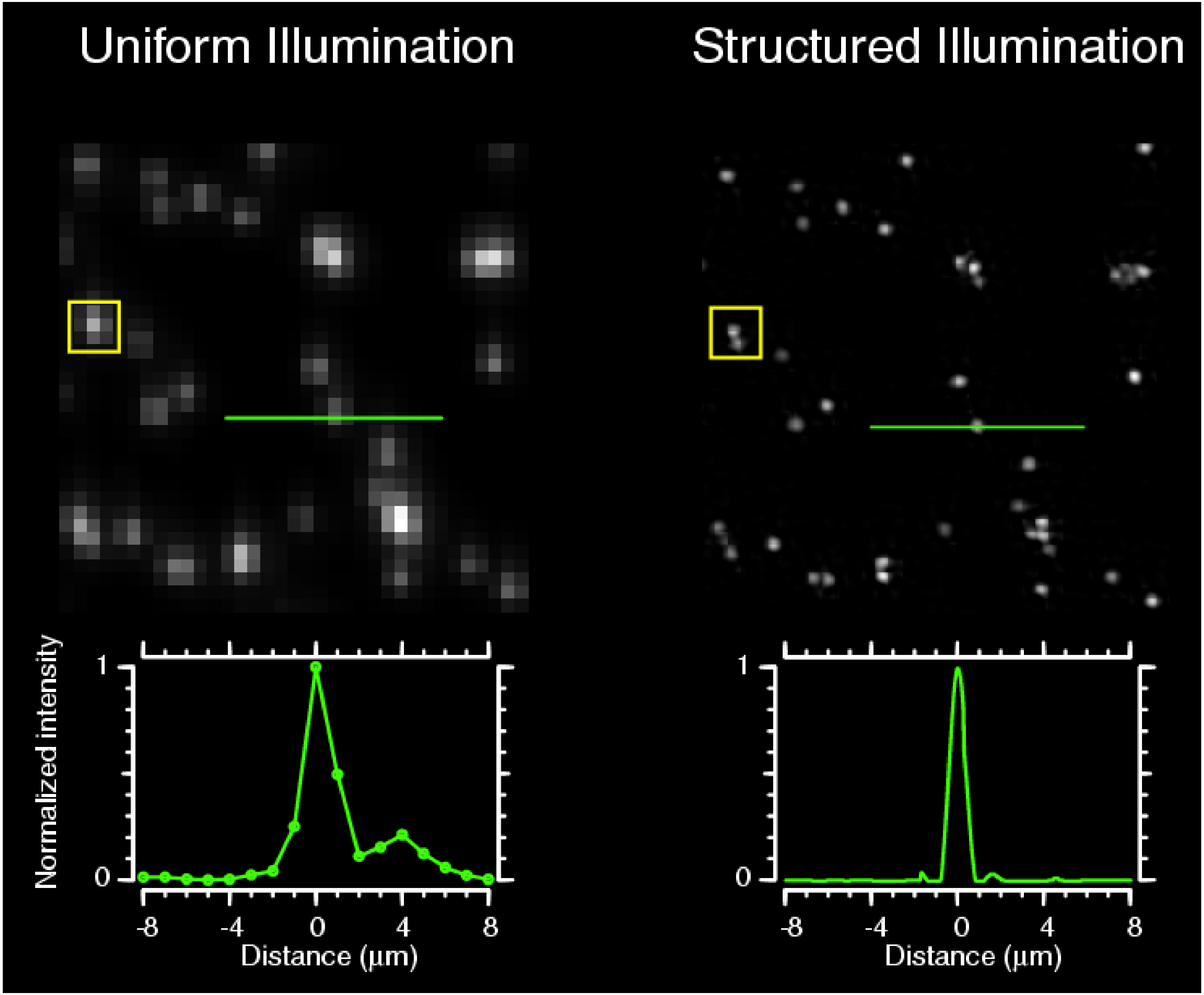


B
8
9
10
11
12
13
14
15
1
2
3
4
5
6
7
E
D
C
Beams

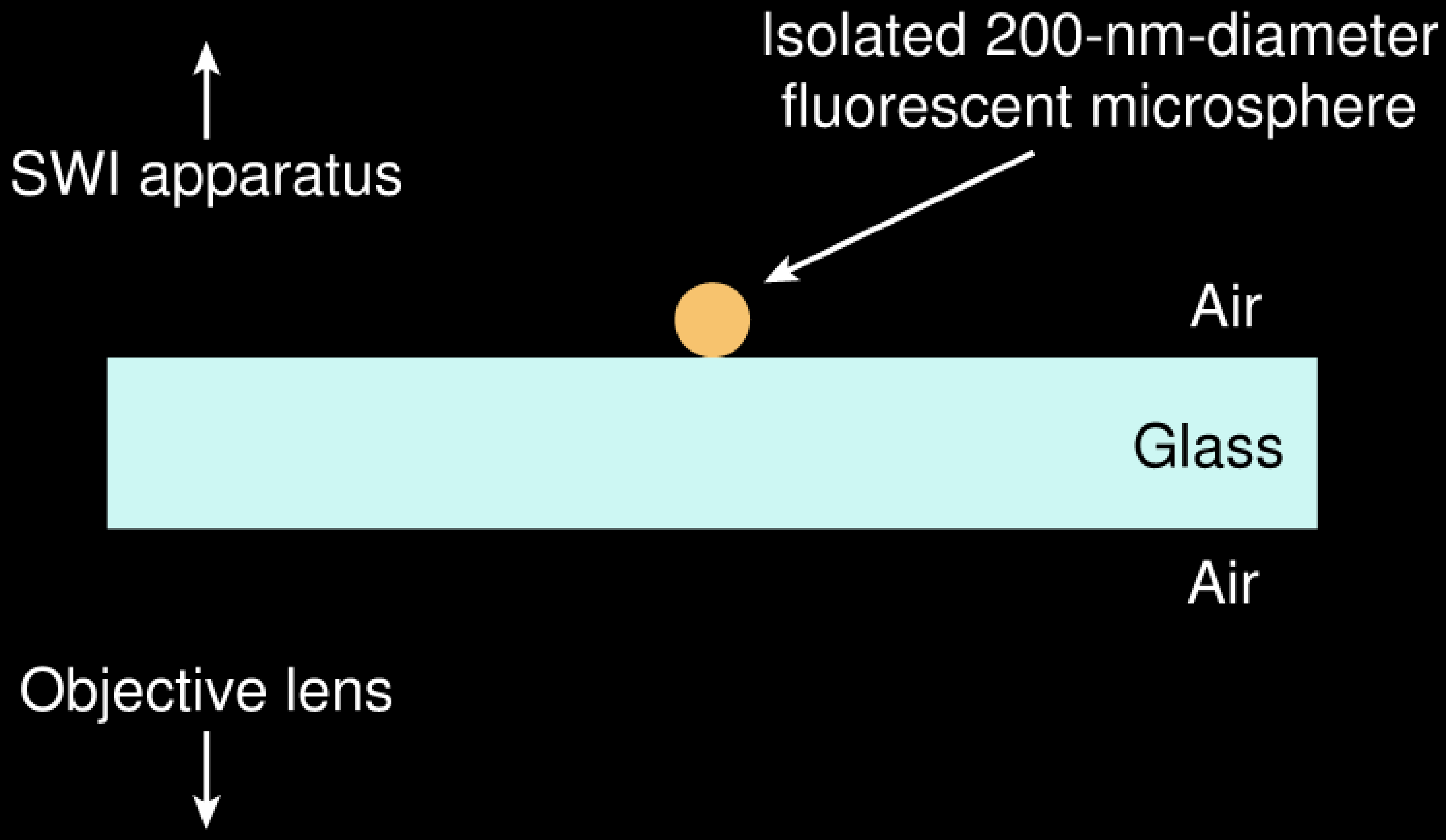


Twinkling decoded into sub-pixel image



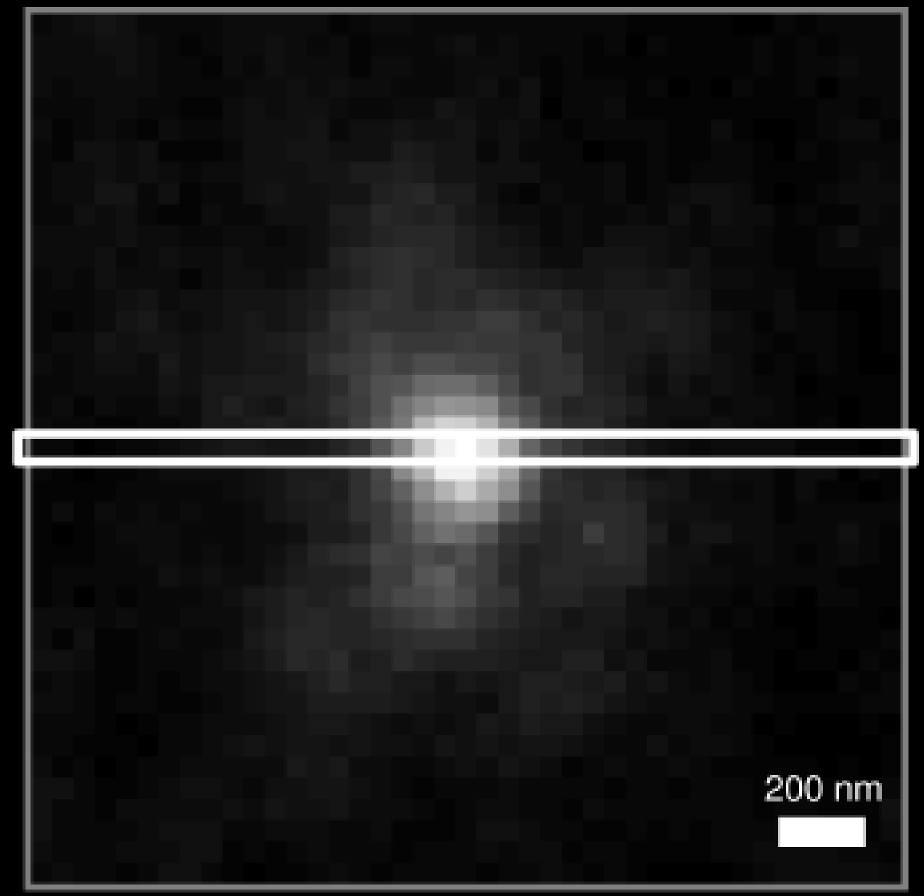

Uniform Illumination
Structured Illumination
Normalized intensity
1
0
-8
-4
0
4
8
Distance (µm)
1
0
-8
-4
0
4
8
Distance (µm)

Measurement of PSF

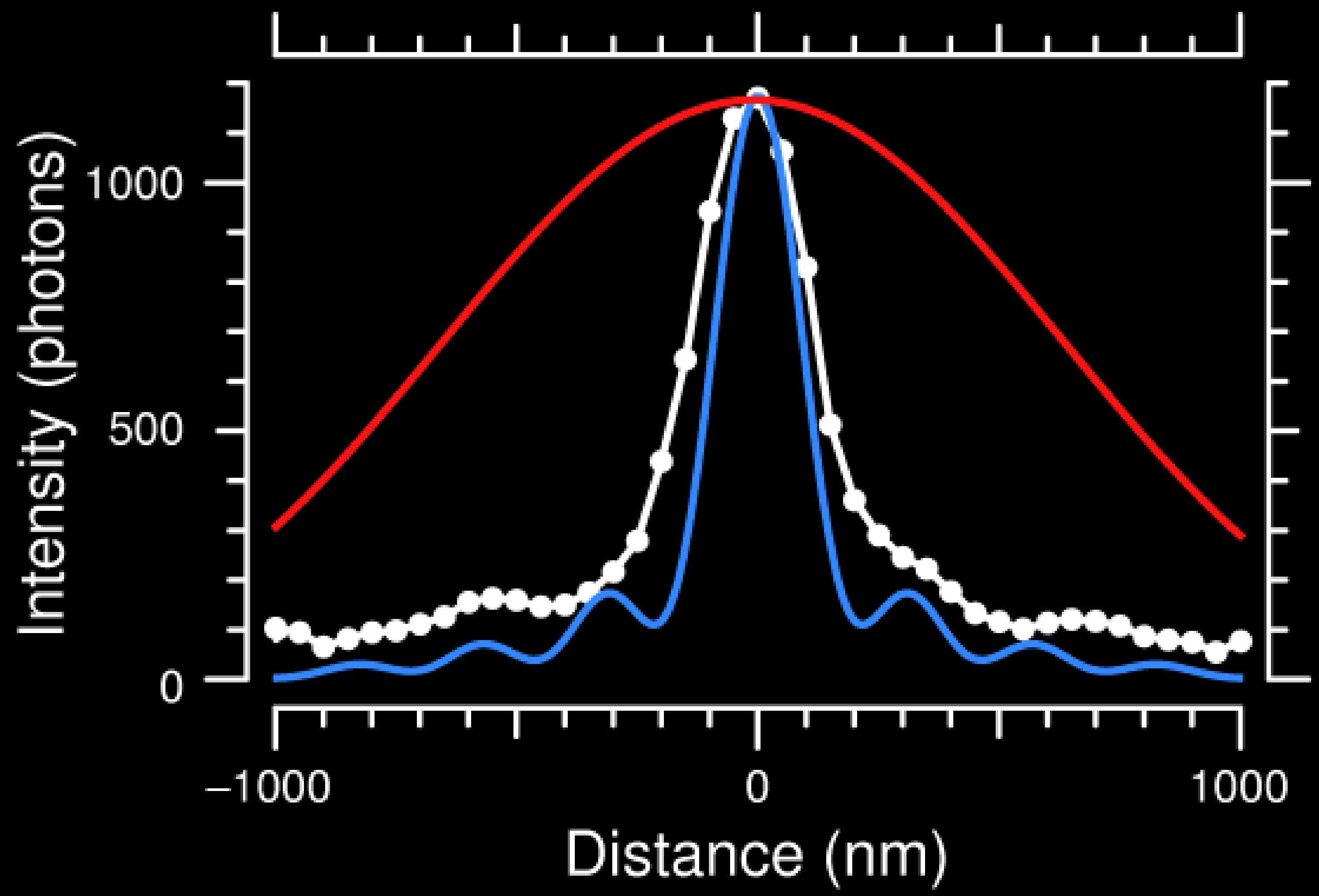


(Cross section, not to scale)

Measurement of PSF



Measurement of PSF



Measured diameter = 290 nm

Predicted diameter = 250 nm

Diameter lens alone = 1,500 nm