Special properties of laser light

1. Monochromaticity. Ultra-narrow spectral bandwidth

\[ P(\omega) \sim P_{\text{laser}}(\omega) \delta(\omega - \omega_0) \]

For pure single frequency,

\[ P(\omega) \sim P_0 \delta(\omega - \omega_0) \]

Laser light has very narrow bandwidth - close to delta function. For visible light - \( \lambda = 500 \text{ nm} \), \( \nu = 6 \times 10^{14} \text{ Hz} \),

Typical laser bandwidth \( \sim 10^4 \text{ Hz} \sim 10^{-5} \text{ Hz} \)

Specially engineered lasers for ultra precision measurements can have \( \Delta \nu \) below 0.01 Hz

Why? - Atomic transition provides gain only near \( \nu_0 \)

Also (usually more important) - Laser cavity provides feedback only at resonant frequencies. These come from discrete frequencies of standing-wave cavity modes.

2. Coherence

a) Temporal coherence. Ultra-narrow bandwidth is synonymous with temporal coherence. Any wave with bandwidth \( \Delta \nu \) can be modelled as a nearly perfect, constant amplitude sine wave for a period of time \( \tau_0 \sim \frac{1}{\Delta \nu} \). Amplitude and/or phase variations occur on the time scale of \( \tau_0 \), the coherence time.
b) **Spatial coherence.** This relates to how different points separated in space are correlated. Since the amplitude/phase is fluctuating, different points may be totally independent, or fluctuate together (coherently). In a light beam, spatial points that are close together are usually correlated strongly (mutually coherent). The area over which this correlation extends is called the coherence area, $S_c$.

\[ \text{Beam diameter} \]

\[ \text{Coherence area} \]

For high-quality laser beams, the coherence area is the entire beam area (as in a plane wave). This is one of the most unique qualities of laser light. All other sources have much smaller coherence area.

High spatial coherence is synonymous with low beam divergence (beam divergence is related to spatial bandwidth in Fourier Optics).

For a coherent beam with diameter $D$, the divergence due to diffraction is
For a partially coherent beam, the divergence is always larger than $\Theta d$. In fact, the actual divergence is related to the coherence area.

Minimum value of $SC$ is $\pi \lambda^2$. This corresponds to an isotropic light source with $\Theta \approx \pi$.

Also true in reverse— for a converging beam (i.e. from a lens), same relation holds for convergence angle and coherence area at minimum spot.

For partial spatial coherence, $d > dc$. For laser light, we get smallest possible spot $d = dc$. 

\[
dc = \frac{1}{\Theta}
\]