The Fundamental Limit to Optical Components

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Is there a fundamental limit to how small we could make an optical component—for example, one that separates beams of different colors or gives us slow-light optical delay? For applications such as wavelength-division multiplexers, we would like smaller, cheaper devices. Nanophotonics offers new opportunities to create them.

For traditional devices, such as Fabry-Perot resonators or gratings, we already have good models to predict performance limits. But for some nanophotonic structures, the only way to design them is by trial and error; we cannot logically separate the functions of the different parts. Simply put, we do not know how they work, so no device model can tell us how well they could work. Since designing nanophotonic structures is computationally hard, we want at least an upper limit so we know when to stop optimization. Intriguingly, empirical designs for layered dielectric superprism wavelength splitters hint strongly at just such an underlying performance bound.[1]

Such a bounding limit should be independent of the details of the structure's design, and should work for large contrasts in refractive index, including even the very large dielectric constants of metals. Constructing such a limit is challenging; the mathematics must include multiple strong scattering. Obvious approaches such as summing series typically do not converge, for example.

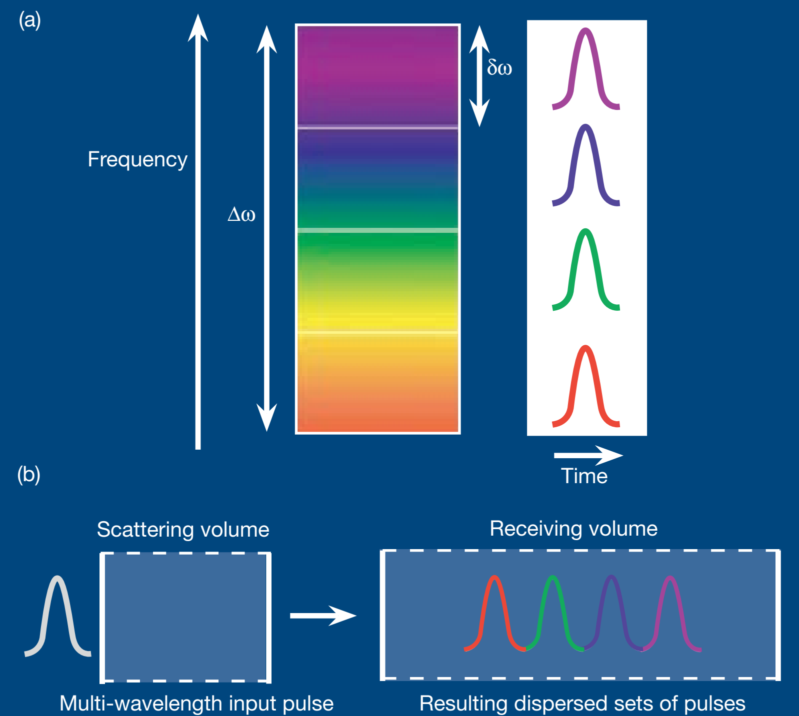
We recently proved a general theorem for such strong multiple scattering,[2] which can be generally stated for linear systems, and can give simple bounding limits for optical components. We also showed explicitly how it can be applied to one-dimensional structures, such as dielectric stacks or single-mode waveguides.

The idea behind the limit is to find a bound to the number of mathematically orthogonal functions that could be generated in a receiving volume as a result of the scattering of an incident wave by a scatterer (i.e., the optical device). Surprisingly, with only minor restrictions, there is quite a specific answer for such a bound.

We can ask, for example, how many distinct colors of pulses can be separated in time (i.e., dispersed) by passing through a one-dimensional structure (see figure). The upper bound to that number is essentially the length of the structure in wavelengths times the magnitude of the largest dielectric constant variation anywhere in the structure, completely independent of the details of the design. An example one-dimensional glass/air structure that would disperse pulses of 32 center wavelengths in the C-band must be at least 41.7 μm thick.

This same result also bounds the performance of fixed linear slow-light structures, including both photonic nanostructures and atomic vapors, where it limits the number of bits of delay with an almost identical product formula.[3]

We expect to be able to extend the use of this broad theorem to 2D and 3D structures to give broad limits to the possible performance of a wide range of optical components, including photonic crystals and other nanophotonic structures.



(a) Pulses of different center frequencies, shown both in frequency and in time.
(b) Conceptual structure of a device (the scattering volume) to separate the pulses at the output (the receiving volume).

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References

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