

Analogy of Wave Phenomena in Optics and Acoustics

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This paper explores structural analogies between electromagnetic waves in the optical domain and mechanical waves in the acoustic domain. By comparing fundamental parameters such as complex and frequency dependent impedance and refractive index, we can establish a framework for transferring methodological expertise between laser physics and ultrasound engineering.

1 Introduction

Light is a transverse electromagnetic wave requiring no medium for propagation, sound is a longitudinal (and transverse) mechanical wave requiring a medium. Despite the fundamentally different physical mechanisms underlying electromagnetism and acoustics, both follow structurally identical physical laws, such as the Fresnel equations or the Fourier analytics. This striking mathematical parallelism suggests that advanced techniques, e.g., diagnostic, imaging or pulse shaping, developed in one field can be directly adapted to the other.

2 Complex and Frequency Dependent Impedance

To bridge both domains, the complex wave impedance serves as the core physical parameter.

In acoustics, the specific acoustic impedance Z_s is given by:

$$Z_s = \rho c_s = r_n + i x_n, \quad (1)$$

where ρ [kg/m³] is the density and c_s [m/s] being the speed of sound; and r_n , x_n represent resistance and reactance (see Eq. (6.5.4) in reference [1]).

Analogously, the optical field impedance Z in a medium is defined as:

$$Z = \mu c', \quad (2)$$

with $\mu = 1.26 \cdot 10^{-6}$ [N/A²] representing the magnetic permeability and c' [m/s] being the phase velocity of light in a medium.

Since $c' = c_0/n$, where $c_0 = 3 \cdot 10^8$ m/s is the constant maximum speed of light, Z relates directly to the complex and frequency dependent refractive index n , with

$$n(\omega) = n'(\omega) + i n''(\omega) = \mu c_0 / Z(\omega). \quad (3)$$

3 A few numbers

To illustrate the practical magnitudes of these parameters, we evaluate two representative physical systems: a 40 kHz acoustic transducer [2] and a 400 THz optical few-cycle laser source [3]. We show the acoustic and optical wavelength, refractive index and impedance for the two systems.

An acoustic analogue to the refractive index n_s is introduced using water as the reference medium ($c_r = c_{\text{water}}$):

Medium	Air	Water	Glass	Silicon
c_s [m/s]	343 [4]	1484 [4]	5300 [5]	7180 [4]
λ_s [mm]	8.58	37.1	132.5	179.5
Z_s [Ns/m ²]	413 [6,7]	1481 k [8]	11 M [9]	16 M [10]
$n_s = c_r/c_s$	4.33	1	0.28	0.21

Tab. 1 Acoustics: For these values, the speed of sound and the density are needed to calculate the wavelength, the impedance and a “refractive index” that is here calculated with a reference speed of sound c_r for water. Note: $c_s = \lambda_s f$, $f = 40$ kHz [2].

Medium	Air	Water	Glass	Silicon
c' [10 ⁸ m/s]	3	2.26	2.07	0.81
λ' [nm]	750	563	517	202
Z [Ω]	376.8	283.31	259.86	101.84
$n = c_0/c'$	1	1.33 [12]	1.45 [13]	3.7 [14]

Tab. 2 Optics: Since the speed of light, the wavelength, and the impedance scale directly with the material's refractive index, only n is needed in order to calculate their values. Note: $c' = \lambda' \nu$, $\nu = 400$ THz [3].

4 Reflection of Waves at Interfaces

Based on the shown impedance values, wave dynamics at material boundaries can be analysed using the reflection coefficient. Assuming only real

impedences, the reflection coefficient for acoustic waves is given as (Eq. (6.2.8) in reference [1]):

$$R_a = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (4)$$

The same is the case for the reflection coefficient of optical waves, which can be simplified into an expression including only the refractive index n , since $Z \propto 1/n$:

$$R_o = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{n_1 - n_2}{n_1 + n_2} \quad (5)$$

5 Time Bandwidth Product

Beyond spatial boundary behaviour, a manifestation of the parallelism is the time-bandwidth product: a few-cycle pulse, whether optical or acoustic, mathematically demands a broad frequency spectrum. For example, a few-cycle optical pulse with a Fourier limited “Full Width at Half Maximum” (FWHM) of $\tau_{fwhm} = 4.42$ fs at a central frequency of $\nu = 400$ THz [3] has a broadband spectrum, see Fig. 1:

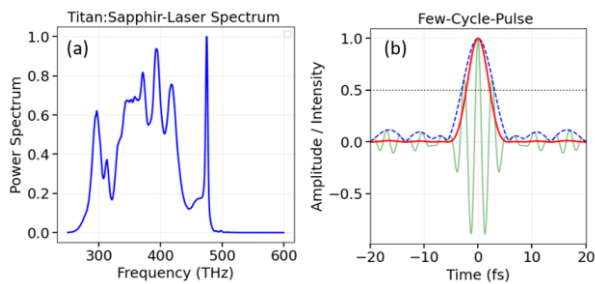


Fig. 1 (a) Normalized power spectrum $|E(\nu)|^2$ of a Ti:Sa laser. (b) Real part of the Fourier Transformation of the spectral amplitude $\text{Re}\{E(t)\}$ (green), temporal amplitude $|E(t)|$ (blue dashed line), and pulse intensity $\sim |E(t)|^2$ (red).

Similarly, a broadband acoustic pulse centred around $f = 40$ kHz [2], has a pulse duration of $\tau_{fwhm} = 92.15$ μ s, see Fig. 2:

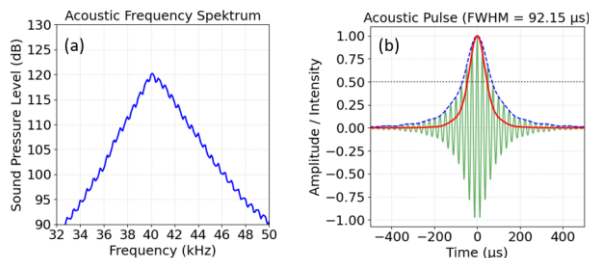


Fig. 2 (a) Normalized power spectrum $|E(\nu)|^2$ of an acoustic transducer working at $f = 40$ kHz. (b) Real part of the Fourier Transformation of the spectral amplitude $\text{Re}\{E(t)\}$ (green), temporal amplitude $|E(t)|$ (blue dashed line), and pulse intensity $\sim |E(t)|^2$ (red).

6 Conclusion

We have demonstrated structural and mathematical analogies between acoustics and optics. By mapping parameters like acoustic and optical impedance, researchers can systematically translate methods across domains. For instance, diagnostic application methods such as Optical Coherence Tomography (OCT) [15] share deep operational principles with Scanning Acoustic Microscopy (SAM) [16]. This synergy between sound and light opens up new pathways and can e.g., also be combined in sono-phonic applications like light deflection on air-based optical ultrasound devices [17,18].

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