

Short Communication

Changes in Laser Wavelengths Entering the Skin Due to Changes in Refractive Indices

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Abstract

Laser light is generated within laser cavities by the stimulated emission of photons. The frequency (and wavelength) of the emissions is determined by the electronic characteristics of the laser medium's atoms. Only certain energy level differences within atoms will generate photons according to quantum physics. In this letter we aim to point out that the absorption and scattering events which occur within tissues are dependent on the incident photon's frequency and not the wavelength, as is often quoted.

Keywords: Laser; Skin; Refractive Index; Complex Refractive Index

Refraction of Light in the Skin

In general, any laser's quoted output wavelength is that found in a vacuum where the refractive index, 'n', is exactly 1.0. However, as soon as the photons enter another medium with a higher refractive index, the induced response from the medium's atoms effectively makes the light appear to travel at a lower velocity, c_m , equal to c/n , where 'c' is the speed of light in a vacuum and 'n' is the refractive index of the medium. (For a more detailed description of this process please go to Richard Feynman's excellent treatise at feynmanlectures.caltech.edu/I_31.html). Since the frequency cannot change (it is fixed by the source's atomic structure) the wavelength must also change - it reduces according to the simple equation $c_m = f \lambda_m$, where 'f' is the frequency of the light and λ_m is its wavelength in that medium. The frequency is determined at source by the photon energy, E_{ph} , by the relation $E_{ph} = (E_{excited\ state} - E_{initial\ state}) = hf$, where 'h' is Planck's constant and the two energies refer to the states an electron may occupy in the emitting atom (identical for all atoms of the same chemical element).

The refractive index of any medium is composed of two components [1]. The real, nonzero refractive index, n' , defined as the ratio of the speed of light in a vacuum to the phase velocity of light in that medium and the imaginary component, k , which determines the extinction coefficient and specifies the absorption coefficient, $\mu_a = 4 \pi k / \lambda_m = 4 \pi k f / c_m$ (the adjective, 'imaginary' comes from the underlying mathematical details - this number has very real consequences!). The Complex Refractive Index (CRI) is given by $n = n' - ik$. Knowledge of the CRI in biological tissues can yield the scattering coefficients (from n') and the absorption coefficients (from k) [2].

When laser energy enters the skin it traverses from the air (with a refractive index of approximately 1.0) into a water/tissue environment with a range of real refractive indices ($n_{stratum\ corneum} = 1.553$, $n_{epidermis} = 1.41-1.494$, $n_{dermis} = 1.36-1.414$, $n_{blood} = 1.335$). Only the real components of the RI are shown here since they are directly responsible for the shift in wavelengths.

As a consequence of refraction $n_1 \lambda_1 = n_2 \lambda_2 = n_i \lambda_i$ for any refractive index n_i and wavelength λ_i . It is, therefore, very simple to calculate the change in wavelength as the light traverses through various media with different refractive indices.

Fig. 1 indicates the wavelength changes for five laser wavelengths commonly used in modern-day laser-skin treatments. While

this may, at first, appear to throw our ideas about absorption to the wind, it does not. Absorption and scattering are frequency-based processes, not wavelength. Quantum mechanics shows that the probability of absorption of photons (and scattering) depends on the frequency of the photons 'matching' the available electronic energy transitions in the absorber's atoms. Materials with a 'high' absorption coefficient are those which have many available electron energy transitions matching the incoming light energy frequency. If these transitions do not match the photons' frequencies, then the material is deemed to have a low absorption coefficient and hence, a low probability of absorption (although not necessarily 'zero') (Table 1).

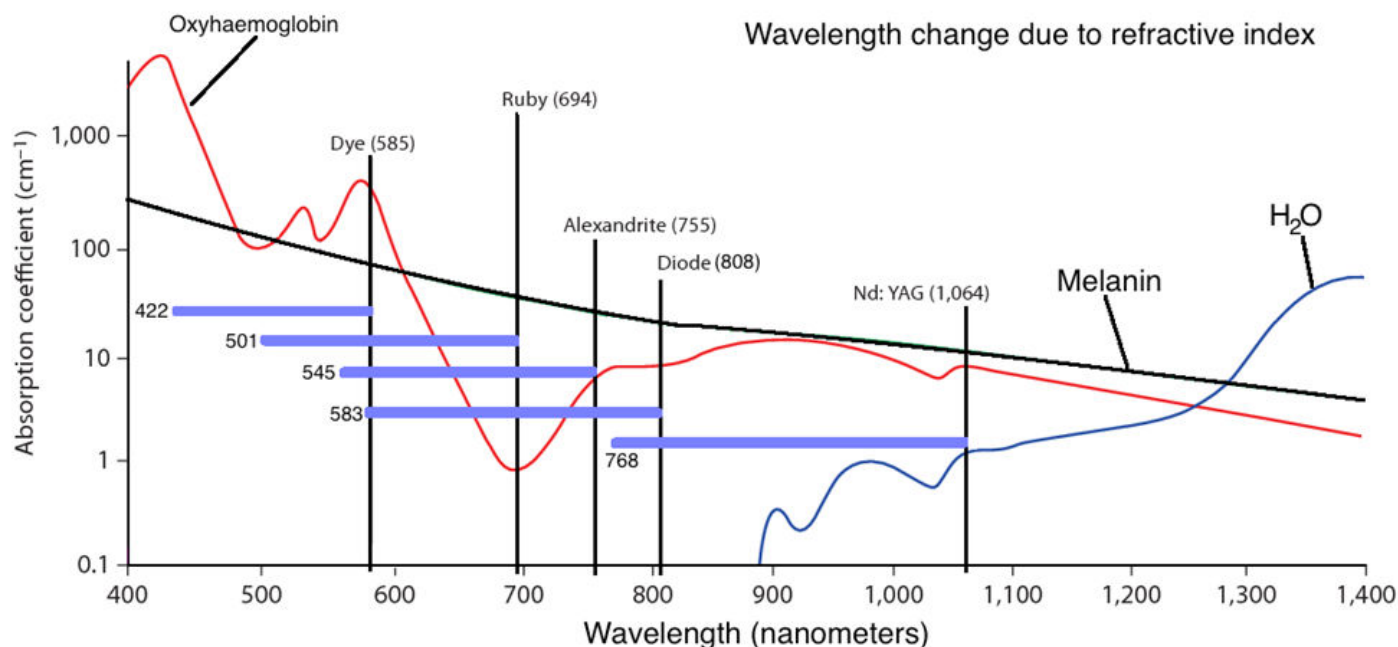


Figure 1: A representation of the shift of wavelengths within the skin due to refractive changes - the vertical lines indicate the vacuum wavelengths for these lasers, while the blue horizontal lines show the change in wavelength due to refraction within the dermis. Note that the wavelength axis is not linear and the absorption curves are approximations. The refractive index for the dermis was averaged to 1.385 in this example.

Laser	Fundamental Wavelength in a Vacuum (nm)	Wavelength in the Dermis (nm)
Nd:YAG (2 nd harmonic)	532	384
PDL	585 / 595	422 / 430
Ruby	694	501
Alexandrite	755	545
Diode	808	583
Neodymium:YAG	1064	768
Holmium:YAG	2100	1516
Erbium:YAG	2940	2123
CO ₂	10600	7653

Table 1: The change in wavelength due to the refractive index change between air ($n=1$) and the dermis ($n=1.385$).

The simple Bohr model of the atom dictates that photon energies may be absorbed if an electron can 'use' that energy to 'jump' to a higher orbit. The electron will drop back into its standard orbit releasing the energy either as a new photon of the same frequency (a scattered photon) or as kinetic (thermal) energy into the surrounding medium (known as 'phonons'). If, however, a suitable electronic transition does not exist (i.e. if the probability of absorption is very low) then the electrons will not become excited and the photons will not likely interact with that atom. In solids the mutual interaction of very many atoms makes the situation more complicated but similar ideas apply in practice, whose net consequences are shown in the absorption curves of Fig. 1.

The Changes in Laser Light Characteristics When It Enters the Skin

Interaction with the medium also changes the incident laser light when it enters the skin. The three defining properties of laser light are its monochromaticity, its high spatial and temporal coherence and its low divergence. When the photons are absorbed they may be re-emitted randomly in any direction (scattered), with their subsequent propagation directions determined by the anisotropy of the medium [1]. Hence the divergence increases rapidly with each scattering event. As a result of scattering, much of the original coherence is also lost since each scattering site essentially becomes a new source of photons. The relatively high incidence of back-scattering appears to confirm this (up to 60% for near infrared photons) [3-6]. However, assuming elastic scattering events, the light remains monochromatic. Given that two of the three fundamental requisites for laser light are lost due to scattering, the remaining light energy cannot truly be considered as 'laser' light. After a few scattering events, the light energy within the dermis is essentially indistinguishable from a high-intensity, non-coherent source passing through a very narrow band-pass filter.

Conclusion

This simple explanation of the photon absorption process in tissues does not change any of the understanding of laser-tissue interactions such as selective photothermolysis or ablative processes. However, it does highlight that the absorption process is not wavelength-dependent even though, in medical laser discussions, we generally use wavelength to parameterize the position in the electromagnetic spectrum. We not suggesting any change in treatment parameters or protocols. Our letter is merely intended to 'clarify the physics' behind many of today's laser treatments of the skin. We feel that it would benefit clinical laser users if they better understood the physical processes occurring during laser treatments. However, the theory of Selective Photothermolysis is based on 'matching' the applied wavelength with the peak (or close) absorptions of the target chromophores. When investigating the literature on these absorption coefficients, it is often not explicitly stated whether the absorbing targets are in a water or air environment during measurements. As we discussed in this short report, this would clearly have an impact on the absorption curves and their peaks due to the change in refractive indices. In doing so, we may find more optimal, alternative wavelengths to apply to various targets.

Conflicts of Interest

The authors declare no conflict of interest in this paper.

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