Reply to Elsässer's Comment on "How many principles does it take to change a light bulb ... into a laser?"

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Abstract. In his Comment, Elsässer claims that the answer to my titular question is one, not four as I have it. He goes on to give the singular principle that supposedly captures the difference between a light-bulb and a laser: $g^{(2)}(\tau = 0) = 1$. His claim is unconsidered and wrong; his proposed principle is impossible to apply and, when corrected, redundant (it then becomes one of the four I list already); his arguments are manifestly misdirected. My paper stands as is.

1. My paper

My paper [1] addressed the question: "what are the fundamental features that distinguish laser light from thermal light?" By the latter I mean the light emitted by a hot body, such as an old-fashioned (incandescent) light bulb. This is apparent from my title and also clearly explained in my paper. I identified four necessary fundamental features (here in qualitative form):

(i) High directionality;

(ii) Monochromaticity;

(iii) High brightness;

(iv) Stable intensity.

I explained how to quantify these features and considered these typical devices: a single-mode laser with power of 100 mW, a linewidth Γ of 10^7 s^{-1}, and a wavelength λ_0 of 1 micron; and a light bulb with filament area $A = 15$ mm^2, and a peak-spectral wavelength $\lambda_{\rm max}$ of 1 micron. The comparison was as follows:

(i) Laser light is polarized and has a single transverse mode; light-bulb light is unpolarized and is emitted into something like $A/\lambda_{\rm max}^2 \sim 10^7$ transverse modes.

(ii) Laser light is monochromatic, with $\Gamma/\omega_0 \sim 10^{-8}$; light-bulb light is broad-spectrum with $\delta\omega \sim \omega_{\rm max}$.

(iii) Laser light is intense, with $\nu \sim 10^{12}$ photons per coherence time; light-bulb light has $\bar{n}_{\rm th}(\omega_{\rm max}) \approx 0.2$ photons per spatio-temporal mode at spectral peak.

(iv) Laser light has a stable intensity, with photocount uncertainty $\delta N \ll \bar{N}$ over time intervals long enough that $\bar{N} \gg 1$; light-bulb light, if collimated and filtered, would have a photocount uncertainty δN larger than $\bar{N}$ for time intervals $\lesssim \Gamma^{-1}$.

2. Elsässer's claim and principle

Elsässer [2], in contrast to me, claims that only one principle is necessary to "understand the difference between ... a light bulb and a laser":

> thermal light showing a central second order correlation $g^{(2)}(\tau = 0)$ value of two is confronted with that of a value of unity for laser light.

This claim and principle may be "simple, elegant, clear and unique", as he says, but it is also unconsidered, wrong, inapplicable, and redundant (when made applicable).

Elsässer's claim is *unconsidered* in that his principle presupposes the existence of a beam so that the second-order correlation function for photon-counting $g^{(2)}$ is a function of only a single coördinate (which he labels as τ). That is, Elsässer has implicitly assumed my first principle even while claiming it to be unnecessary.

Elsässer's claim is *wrong* in that it is simple to imagine a type of light that satisfies his principle $g^{(2)}(\tau = 0) = 1$ but which could not possibly be considered laser light. As

Elsässer notes, non-classical light can exhibit $g^{(2)}(0) < 1$. An example of a system that can achieve $g^{(2)}(0) < 1$ is the radiation emitted by a single atom (considered at a single point in the radiated field, for example). Consider a detector behind a pin-hole in a screen close to such an atom. If there is, on the same side of the screen as the atom, but a long way away, a light bulb, then the $g^{(2)}(0) = 2$ thermal light will add incoherently to the $g^{(2)}(0) < 1$ atomic fluorescence. Clearly this sum could be made as close as desired to $g^{(2)}(0) = 1$, but that doesn't mean that suddenly one has made a laser beam!

Elsässer's principle is *inapplicable* in that $g^{(2)}(\tau = 0) = 1$ is an unachievable ideal. Indeed he goes on to say that a laser has Poissonian statistics, which implies the even stronger condition $g^{(2)}(\tau) = 1$ for all τ. This is certainly not true for real lasers, as is manifest in the fact that at low frequencies technical noise is far larger than the Poissonian or shot noise of the ideal laser Elsässer imagines. We could replace Elsässer's inapplicable $g^{(2)}(\tau) = 1$ by $g^{(2)}(\tau) \approx 1$ — that is, $|g^{(2)}(\tau) - 1| \ll 1$ — which can still be true even with large technical noise. However $g^{(2)}(\tau)$ could, in principle, take values quite different from one only on a set of arbitrarily small measure on the real line and this would have arbitrarily small observable consequences. A less stringent requirement is that a suitable *average* of $g^{(2)}(\tau)$ is very close to one over *any* interval $[0, T]$ such that $\bar{I}T \gg 1$. The physical significance of this condition is as follows. The uncertainty δN in the number of photons in an interval $[0, T]$ is given by

$$(\delta N)^2 = \int_0^T ds \int_0^T dt \left\{ \bar{I}^2 [g^{(2)}(s-t) - 1] + \bar{I}\delta(s-t) \right\} \tag{1}$$

$$= \bar{N} + \bar{N}^2 [\bar{g}_T^{(2)} - 1], \tag{2}$$

where $\bar{N} = \bar{I}T \gg 1$ is the mean number of photons in that interval and $\bar{g}_T = T^{-2} \int_0^T dT' \int_0^{T'} d\tau g(\tau)$. Thus, if and only if $\bar{g}_T \approx 1$, we have $\delta N \ll \bar{N}$.

Elsässer's principle, when made physically applicable in the above way, is thus *redundant*. The condition that this average of $g^{(2)}(\tau)$, over any interval large enough to contain a macroscopic field (many photons), be close to unity, is implied by my condition (iv), that the laser have a stable intensity.

3. Elsässer's subsequent arguments

Following the above, Elsässer seems to take aim at my principles (ii) and (iii), saying (my emphasis added)

> *only considering* the spectral properties in terms of the first order (field) correlation $g^{(1)}(\tau = 0)$ obtained via the Wiener-Khintchine theorem is no longer a criterion for differentiating between thermal and laser light.

If this is his aim, he misses wildly. First, $g^{(1)}(0) = 1$ by definition, for any field, so it can not be used as a criterion for anything. Second, while my principles (ii) and (iii) do involve the first-order correlation $g^{(1)}(\tau)$, the latter principle cannot be stated in terms of this correlation function alone. Third, it could not be more explicit in my paper that

I characterise laser light by a *conjunction* of four features. I am never “only considering” one of my principles.

Similarly, when Elsässer turns at last to my principle (i), saying

> directionality is no longer a unique criterion for laser light because amplified spontaneous emission originating from semiconductor-based optoelectronic light emitters with waveguides unifies broad-band and directionality and does exhibit photon bunching, i.e. thermal light second order coherence characteristics.

he seems to have forgotten the title of his own paper (quoting, as it does, the title of mine). The question is not, “how many principles does it take to change *amplified spontaneous emission originating from semiconductor-based optoelectronic light emitters with waveguides* into a laser?” It is “how many principles does it take to change a *light bulb* into a laser?” The fact that amplified spontaneous emission originating from semiconductor-based optoelectronic light emitters with waveguides has “thermal light second order coherence characteristics” does not mean that it is thermal light, like that from a light bulb. Glauber [3] used the term *incoherent light* to refer to light with the same intensity correlations as thermal light, regardless of its other properties, as I discuss in my Conclusion. The whole of my Section 4 addresses the point that it is possible to have light that satisfies my first three principles, while remaining incoherent in terms of its intensity correlations. Elsässer is attacking a straw man.

4. Discussion

Elsässer’s fixation on $g^{(2)}(0) = 1$ as *the* defining feature of a laser is certainly not supported by scientists who have sought to communicate the importance of the laser to the public. As I quoted in my paper, the official *Year of Light* (2015) home page [4] says (my emphasis added).

> A laser is an optical amplifier — a device that strengthens light waves. Some lasers have a *well-directed*, *very bright* beam with a *very specific color*; others emphasize different properties, such as extremely short pulses. The key feature is that the amplification makes light that is very *well defined and reproducible*, unlike ordinary light sources such as the *sun or a lamp*.

The sources with which a laser is contrasted are thermal (in all respects). The first three features I list appear prominently‡. The fourth feature, a stable intensity, is referenced obliquely, at best, if it is covered by the phrase “well defined and reproducible”.

‡ It is true that they are listed as properties only of “some lasers”, and the other example given, of a laser producing extremely short pulses, is clearly not monochromatic, the qualitative statement of my criterion (ii). However, the most useful lasers producing extremely short pulses have a locked carrier-envelope phase [5], and would still satisfy my quantitative criterion (ii), $\Gamma \ll \omega_0$, if the linewidth Γ is taken to be the width of the narrow peaks within the broad spectrum, rather than the width of the broad spectrum itself.

To conclude, Elsässer's comment has no bearing on the correctness, relevance, or cogency of my paper. I hope that, in time, it will repay his closer attention.

References

[1] H. M. Wiseman. How many principles does it take to change a light bulb ... into a laser? *Physica Scripta*, 91(3):033001, 2016.

[2] W. Elsässer. Comment on "How many principles does it take to change a light bulb into a laser?". arXiv:1607.03647, 2016.

[3] Roy J. Glauber. Photon correlations. *Phys. Rev. Lett.*, 10:84–86, Feb 1963.

[4] Lasers. `http://www.light2015.org/Home/LearnAboutLight/Lasers.html`, 1st August 2015.

[5] David J. Jones, Scott A. Diddams, Jinendra K. Ranka, Andrew Stentz, Robert S. Windeler, John L. Hall, and Steven T. Cundiff. Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis. *Science*, 288(5466):635–639, 2000.