Reply to "Comments on Intensity Enhancement in Textured Optical Sheets"

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Abstract—**The recent comments[1] on the above paper[2] are self-contradictory and are physically incorrect. The comments violate the principle of time-reversal invariance for the Fresnel transmission and reflection coefficients of light rays. The proposed alternate formula for the intensity enhancement in optical media is an overestimation that violates the first and second laws of thermodynamics.**

There has been considerable interest in the prospect of improving the performance of light detectors and solar cells through trapping the incident light by total internal reflection in the active semiconductor material. In a paper [1] published in this TRANSACTIONS it was shown that the internal light intensity could be enhanced by the factor $2n^2$ and the effective internal path length for absorption could be enhanced by $4n^2$ (where n is the index of refraction). This has led to a considerable improvement in the short-circuit current of amorphous silicon solar cells [2] and is expected to lead in the near future to a new generation [3] of ultrathin high-efficiency crystalline silicon solar cells.

In a recent comment [4] on this paper [1], it was claimed that the intensity enhancement factor of $2n^2$ is too high and the correct intensity enhancement factor should be $8n$. These comments are self-contradictory mathematically and in violation of physical principle:

1) The comments are self-contradictory since the factor $8n \geq 2n^2$ for all indices of refraction $n \leq 4$. Therefore, the newly proposed enhancement factor $8n$ is actually greater than the original $2n^2$ factor for virtually all known semiconductor materials, i.e., all semiconductors with an index of refraction $n \leq 4$.

2) The comment violates the principle of time-reversal invariance by explicity assuming that the Fresnel transmission coefficient [5], [6] for light incident on the medium is unequal to the Fresnel transmission coefficient for light to escape from the medium, i.e., $T_{inc} \neq T_{esc}$.

3) The comment violates energy conservation by approximating the transmission coefficient for incident light as $T_{inc} \approx 4/n$ which is greater than unity for all $n \leq 4$. This implies light transmission *greater* than the amount of incident light which violates energy conservation. At the same time the transmission coefficient for escaping light is approximated as $T_{esc} \approx 1$.

4) The combination of the errors and inappropriate approximations listed above would violate the second law of thermodynamics. Due to the excessively high intensity enhancement factor $8n \geq 2n^2$, a black speck in the optical medium would reach equilibrium at a temperature greater than the temperature of the radiation field in which the optical medium is immersed.

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[1] T. C. Paulick, *IEEE Trans. Electron Devices*, vol. ED-32, no. 7, p. 1361–1362, July 1985.

[2] E. Yablonovitch and G. D. Cody, *IEEE Trans. Electron Devices*, vol. ED-29, no. 2, pp. 300–305, Feb. 1982.

In conclusion, the comment leads to an excessively high enhancement factor due to incorrect and inappropriate approximations for the Fresnel transmission coefficients into and out of the optical medium.

References

[1] E. Yablonovitch and G. D. Cody, "Intensity enhancement in textures optical sheets for solar cells," *IEEE Trans. Electron Devices*, vol. ED-29, pp. 300–305, Feb. 1982.

[2] H. W. Deckman, C. R. Wronski, H. Witzke, and E. Yablonovitch, "Optically enhanced amorphous silicon solar cells," *Appl. Phys. Lett.*, vol. 42, p. 968, 1983.

[3] R. A. Sinton, Y. H. Kwark, S. Swirhun, and R. M. Swanson, "Silicon point contact concentrator solar cells," *IEEE Electron Device Lett.*, vol. EDL-6, p. 405, 1985.

[4] T. C. Paulick, "Comments on 'intensity enhancement in textured optical sheets,' " *IEEE Trans. Electron Devices*, vol. ED-32, p. 1361, 1985.

[5] R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, vol. 1. Reading, MA: Addison-Wesley, 1963, p. 33–37.

[6] V. Dixit, J. Lodenquai, and J. McTavish, "Flux enhancement and efficiency for photovoltaic cells," *IEEE Trans. Electron Devices*, vol. ED-31, p. 1901, 1984.