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Bass, Michael; Richardson, Martin C.; and Ballato, John, "Response to "Comment on 'Confined propagation and near single-mode laser oscillation in a gain-guided, index antiguided optical fiber'" Appl. Phys. Lett. 102, 026101 (2013)" (2013). *Faculty Bibliography 2010s*. 3667.
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Cite as: Appl. Phys. Lett. **102**, 026102 (2013); <https://doi.org/10.1063/1.4775698>

Submitted: 08 November 2012 . Accepted: 26 December 2012 . Published Online: 17 January 2013

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Response to “Comment on ‘Confined propagation and near single-mode laser oscillation in a gain-guided, index antiguided optical fiber’” [Appl. Phys. Lett. 102, 026101 (2013)]

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(Received 8 November 2012; accepted 26 December 2012; published online 17 January 2013)

[<http://dx.doi.org/10.1063/1.4775698>]

In the comment by Cao *et al.*,¹ they raise an important point concerning Siegman’s original work on index anti-guided fibers.² In that work, Siegman treated the cladding as if it were infinitely thick so that an interface between the cladding and another medium, e.g., air, was not considered. Cao *et al.* point out that if the cladding is not infinitely thick, the cladding–air interface may have to be taken into account when interpreting experimental results such as those we presented in Ref. 3. Though they are correct in suggesting that index guided modes involving the cladding–air interface can potentially oscillate, we insist the evidence for gain guided index anti-guided (GG IAG) lasing conducted by ourselves and published in collaboration with Professor Siegman is indisputable.

The clearest evidence that index guided modes involving the cladding–air interface could not have been present in our experiments is provided in the photo of the end face of the fiber in Ref. 3. That photo shows that the cladding circumference was nicked in several places as a result of the manner in which we cleaved and polished the (soft phosphate glass) fiber end. These non-uniformities were present on both ends of the fiber and would have contributed significant losses to any mode of oscillation involving the cladding–air interface. Hence it is extremely unlikely that an index guided LP₀₀ mode of the cladding–air fiber would have oscillated. In our experiments, we pumped at over 10× threshold and observed the mode to retain properties consistent with those of the LP₀₀ mode of the core of the GG IAG fiber. We have since reported GG IAG results on fibers having cores as large as 400 μm in diameter⁴ and cladding as thick as 100 μm.⁶ The results from these fibers are completely consistent with GG IAG lasing.

In putting Ref. 1 into context, it is important to note that Siegman and ourselves made further contributions to GG IAG laser development after his ground-breaking paper. In 2007, Siegman published Ref. 5 in which he went beyond just pointing out that if there is gain in the core that exceeds the index anti-guiding losses in an anti-guiding fiber that lossless Bessel function modes will propagate. He showed that those Bessel function modes of the fiber that become lossless are significantly re-shaped and confined into the core of the fiber. To quote from Ref. 5, “For larger negative values of ΔN, however, the mode profile within the core

tends asymptotically to a J₀ Bessel function profile that becomes essentially independent of the gain value, with the value of this Bessel function mode profile at the core–cladding interface tending asymptotically toward zero as either ΔN or G increase in magnitude.” In our experiments in Ref. 3 and in our subsequent work |ΔN| = 1256, which is very large. In Ref. 5, Siegman showed that for |ΔN| = 100 the field of the LP₀₀ mode at the core–cladding boundary of an index anti-guided fiber with G = G_{th} is ~0.15× the peak value on the axis of the core. For |ΔN| = 1256, it will be much smaller. Therefore, we can expect no significant leakage of the LP₀₀ mode from the core of the GG IAG fibers in our experiments to reach the cladding–air interface and encourage oscillation of index guided modes at the cladding–air interface.

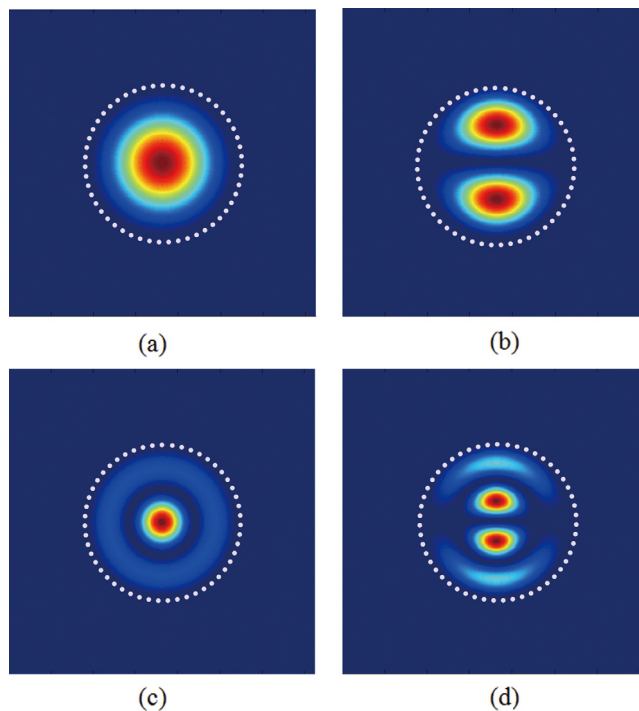


FIG. 1. Calculated intensity profile of (a) LP₀₁, (b) LP₁₁, (c) LP₀₂, and (d) LP₁₂ modes in a GG IAG fiber with a core diameter of 200 μm. The dotted circle indicates the core–cladding boundary. Dark red indicates highest intensity, and dark blue indicates no intensity in that region. Reproduced from Figure 1 with permission from X. Wang, Y. Chen, W. Hageman, G. Kim, M. Richardson, C. Xiong, J. Ballato, and M. Bass, *J. Opt. Soc. Am. B* **29**, 191 (2012). Copyright 2012 Optical Society of America.

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We call attention to the mode patterns presented in Figure 1 taken from Ref. 6. These show that the fields of the GG IAG modes are identical to those of ordinary index guided fibers with zero amplitude at the core cladding boundary as predicted by Siegman in Ref. 5. The index anti-guided modes of the core when gain sufficient for lossless propagation was achieved in fibers with such large values of $|\Delta N|$ as we used would be completely confined in the core. There would be no field in the cladding to encourage the index guided LP_{00} mode of the cladding-air fiber. It is highly unlikely that lasing of a mode involving the cladding-air boundary could have taken place in our GG IAG experiments for both the experimental reason stated above and the mode mismatch indicated in Ref. 5 and in Figure 1. Nonetheless, future experiments should take into account the caution Cao *et al.* make with respect to ensuring the cladding is

sufficiently thick and $|\Delta N|$ sufficiently large so that index-guided modes do not govern lasing. Another approach in future experiments would be to roughen the cladding-air boundary such that index guided modes of the cladding-air interface cannot propagate.

¹J. Cao, W. Wang, L. Huang, S. Guo, and Q. Lu, "Comment on 'Confined propagation and near single-mode laser oscillation in a gain-guided, index antiguided optical fiber [Appl. Phys. Lett. 89, 251101 (2006)],'" *Appl. Phys. Lett.* **102**, 026101 (2013).

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