

This efficiency will, of course, stop increasing when limiting effects such as pump depletion become evident.

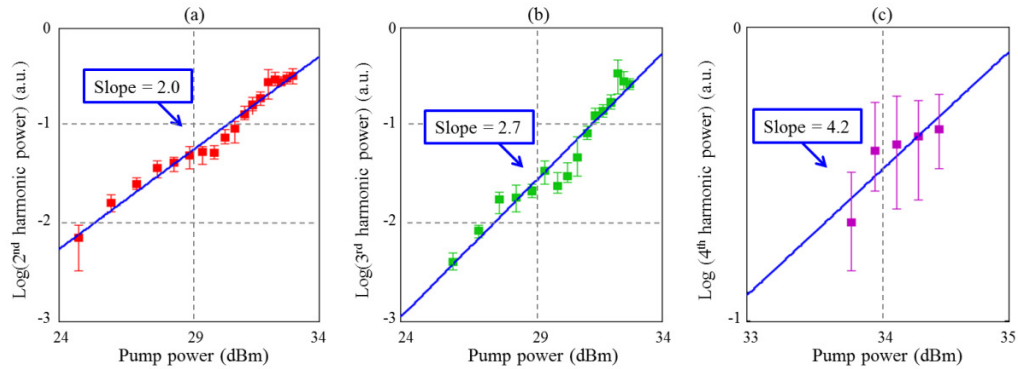


Fig. 7. Measured power of the generated 2nd, 3rd, and 4th harmonics at a pump wavelength of 1550nm, as a function of the pump power are illustrated in d, e, and f, revealing nearly quadratic, cubic and power-of-4 dependency for the 2nd, 3rd, and 4th order processes

We have experimentally confirmed that the mechanism responsible for the observed harmonic generation is cascaded-harmonic generation via $\chi^{(2)}$ processes. This is because the 3rd harmonic is only observed simultaneously with the 2nd harmonic. Similarly, the 4th harmonic is only observed simultaneously with both the 2nd and 3rd harmonics. This suggests that the 3rd and 4th harmonics arise from cascaded $\chi^{(2)}$ processes, as opposed to $\chi^{(3)}$ and $\chi^{(4)}$ effects. This observation is further supported by the fact that third and fourth order nonlinear coefficients are many orders of magnitude smaller than the second order coefficient for lithium niobate [39]. In order to further validate the effectiveness of the employed quasi-phase matching technique, a second lithium niobate whispering-gallery resonator with no crystal poling was fabricated and tested using the same experimental setups. Harmonic generation was not observed in the similar experimental conditions, confirming the significant role of the employed non-uniform poling in providing quasi-phase matching for 2nd, 3rd, and 4th harmonic generation processes.

In conclusion, we experimentally demonstrate continuous-wave cascaded harmonic generation up to the fourth harmonic in a millimeter-scale whispering gallery resonator, allowing four spectral lines which are equally spaced in frequency and span a 2-octave frequency band. Many challenges exist, but we believe this work can be extended toward continuous-in-time extreme nonlinear optics where the electron is repeatedly torn from and recombines with the atom. These challenges include phase matching and concentration of light in the gaseous region near the evanescent tail of the modes discussed here. Still, the first steps in this journey, demonstrated here, can be followed toward the extreme by adding structures such as in [40] as suggested in [41].

Acknowledgments

The authors would like to thank Dr. Harald Schwefel, Prof. Mani Hossein-Zadeh at the University of New Mexico, and Prof. Bahram Jalali's group at UCLA for advice and assistance with the experiment, and Opticology, Inc. for assistance with fabrication. Matthew Tomes is supported by a Graduate Research Fellowship from the National Science Foundation. This work is supported by National Science Foundation ENG-ECCS-065614, and by the Air Force Office of Scientific Research Young Investigator Award under contract number FA9550-10-1-0078.