Extending cavity-enhanced high-harmonic generation with Bessel-Gauss beams

William Putnam, Damian Schimpf, and Franz Kärtner

Novel enhancement cavities might further cavity-enhanced non-linear optics by providing direct access to the intra-cavity focus and increasing the achievable focal intensity.

At high optical intensities, light can modify the optical properties of media and lead to non-linear optical effects, such as harmonic generation. The invention of the laser brought a convenient means to reach such intensities. Indeed, only a year after the construction of the first laser, researchers generated second harmonics by focusing a light beam to an intensity of around 10^7 W/cm^2 in a quartz crystal.¹ As optical sources have evolved, higher optical intensities have become accessible, and higher-order nonlinear optical effects have been observed and used. Above intensities of around 10^{13} W/cm^2 , researchers have uncovered a distinct 'high-intensity' regime of nonlinear optics with promising applications.

In this high-intensity regime, harmonics of the thousandth order and greater can be produced through a nonlinear optical mechanism aptly named high-harmonic generation (HHG). These high harmonics lie in the generally hard-to-reach extreme-ultraviolet (EUV) or soft x-ray spectral region. Currently, the predominant sources in this portion of the electromagnetic spectrum involve large and expensive synchrotrons or free-electron lasers. Future sources based on HHG might provide compact, table-top alternatives for the numerous research, medical, and industrial applications of EUV and soft x-ray light.

To date, complex amplifier chains have been the most popular means for reaching the high intensities necessary for HHG. Commercial amplifiers can routinely produce millijoule-energy laser pulses with durations of tens of femtoseconds, thereby easily achieving intensities exceeding 10^{13} W/cm^2 . The downside of these systems, however, is their low repetition rate. Such amplifiers generally output several thousand or fewer laser pulses per second (around kHz repetition rates), while low-energy pulsed lasers conventionally operate in the millions

Figure 1. (a) Illustration of a Gaussian beam enhancement cavity. Note that the harmonics (purple pulse) are generated co-linearly with the driving beam. (b) The intra-cavity Gaussian mode intensity on the cavity mirrors in the x-y plane. The dashed white circles indicate roughly where two of the cavity mirrors lie. (c) Illustration of a Bessel-Gauss enhancement cavity. This cavity is rotationally symmetric about the z-axis (as indicated by the red circle). Also, note that the harmonics propagate along the z-axis. (d) Intra-cavity Bessel-Gauss mode intensity on the segmented cavity mirror in the x-y plane. The dashed white circles roughly show the boundaries between the different sections of the segmented mirror.

of pulses per second regime (MHz repetition rate). Generating fewer pulses per second translates to fewer high-harmonic pulses per second and, thus, a reduction in EUV or soft x-ray power.

Continued on next page

To circumvent this repetition rate problem, researchers have recently pursued cavity-enhanced HHG.²⁻⁵ In an optical cavity, pulses are passively amplified through constructive interference: after a single round-trip through a resonant cavity, a laser pulse constructively interferes with (adds to) the next pulse in the pulse train. Thus, enhancement cavities can boost intra-cavity intensities to the high-intensity regime while maintaining high repetition rates.

Cavity-enhanced HHG has been demonstrated with tens of microwatts of power per harmonic in the EUV region.^{4,5} However, scaling to even higher harmonic powers, has met several roadblocks. The cavity geometry used in nearly all cavity-enhanced HHG experiments is based on a 'Gaussian beam cavity'²⁻⁵: see Figure 1(a). The intra-cavity Gaussian beam generates harmonics that propagate co-linearly with the beam, so out-coupling the harmonics (that is, getting the harmonics out of the cavity), is an issue. Additionally, for Gaussian designs, the maximum intensity at the intra-cavity focus is limited. The largest achievable intra-cavity spot-size on the cavity mirrors is only around one millimeter: see Figure 1(b). As a result, with mirror damage thresholds around $10^{11}\text{W}/\text{cm}^2$ and a focal spot-size of a few tens of microns (typical for a Gaussian enhancement cavity), the maximum achievable focal intensity is around $10^{14}\text{W}/\text{cm}^2$. To bypass these cavity-geometry issues, we recently proposed a high-intensity enhancement cavity based on Bessel-Gauss beams.⁶

Bessel-Gauss beams can be thought of as superpositions of many tilted Gaussian component beams called decentered Gaussian beams.^{6,7} Decentered Gaussian beams are exact solutions to the paraxial wave equation that closely resemble normal Gaussian beams whose propagation direction is tilted with respect to the optical axis.⁸ If we consider a family of many such decentered beams that all have the same tilt, we see that the propagation directions lie on the surface of a cone. Superposing these beams yields the Bessel-Gauss beam.

In this decentered Gaussian beam picture, designing optical cavities supporting Bessel-Gauss modes is straightforward. If we revolve the basic Gaussian cavity geometry shown in Figure 1(a) about the z -axis, we find a new cavity supporting Bessel-Gauss modes: see Figure 1(c). This follows directly from the construction of Bessel-Gauss beams as superpositions of many decentered Gaussian beams. More details are available elsewhere.⁶ Although the Bessel-Gauss cavity is composed of complex, segmented mirror structures, the cavity avoids the two previously mentioned major obstacles to improved cavity-enhanced HHG. Firstly, on the z -axis the intensity drops to zero at the mirror surfaces, so the Bessel-Gauss cavity offers convenient access to the intra-cavity focus: see Figure 1(d). Large holes can then

easily be placed in the mirror centers for near-perfect out-coupling of harmonics. Secondly, the Bessel-Gauss cavity provides a substantially larger spot-size on the cavity mirrors, so the achievable intra-cavity focal intensity is significantly increased: see Figure 1(d).

Although this example illustrates the relationship between Gaussian enhancement cavities and ones supporting Bessel-Gauss modes, Bessel-Gauss cavities with complex, segmented mirrors may not be the most practical. A confocal Bessel-Gauss cavity has also been designed that uses only spherical mirrors and may provide near perfect out-coupling for high harmonics as well as intra-cavity intensities of $10^{15}\text{W}/\text{cm}^2$ or greater.⁶

In summary, cavity-enhancement is a promising path towards high-repetition rate, high-intensity nonlinear optics, in particular HHG. Bessel-Gauss enhancement cavities might extend the reach of these cavity-enhanced applications by providing improved access to the intra-cavity focus and by supporting significantly higher intra-cavity intensities. There remain challenges to overcome, however, before Bessel-Gauss cavities become practical alternatives to the more common Gaussian ones. These challenges are the focus of our current work. In particular, small mirror-surface imperfections may dramatically affect the performance of Bessel-Gauss enhancement cavities. We are investigating this issue along with its connection to azimuthal mode degeneracy in Bessel-Gauss cavities.

Author Information

William Putnam

Department of Electrical Engineering and Computer Science
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, MA

Damian Schimpf and Franz Kärtner

Department of Electrical Engineering and Computer Science
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, MA
and
Center for Free-Electron Laser Science
German Electron Synchrotron (DESY)
Department of Physics
University of Hamburg
Hamburg, Germany

Continued on next page

References

1. P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich, *Generation of optical harmonics*, **Phys. Rev. Lett.** **7** (4), pp. 118–119, 1961. doi:10.1103/PhysRevLett.7.118
2. R. J. Jones, K. D. Moll, M. J. Thorpe, and J. Ye, *Phase-coherent frequency combs in the vacuum ultraviolet via high-harmonic generation inside a femtosecond enhancement cavity*, **Phys. Rev. Lett.** **94** (19), p. 193201, 2005. doi:10.1103/PhysRevLett.94.193201
3. C. Gohle, T. Udem, M. Herrmann, J. Rauschenberger, R. Holzwarth, H. A. Schuessler, F. Krausz, and T. W. Hänsch, *A frequency comb in the extreme ultraviolet*, **Nature** **436** (7048), pp. 234–237, 2005. doi:10.1038/nature03851
4. J. Lee, D. R. Carlson, and R. J. Jones, *Optimizing intracavity high harmonic generation for XUV fs frequency combs*, **Opt. Exp.** **19** (23), pp. 23315–23326, 2011. doi:10.1364/OE.19.023315
5. A. Cingöz, D. C. Yost, T. K. Allison, A. Ruehl, M. E. Fermann, I. Hartl, and J. Ye, *Direct frequency comb spectroscopy in the extreme ultraviolet*, **Nature** **482** (7383), pp. 68–71, 2012. doi:10.1038/nature10711
6. W. P. Putnam, D. N. Schimpf, G. Abram, and F. X. Kärtner, *Bessel-Gauss beam enhancement cavities for high-intensity applications*, **Opt. Exp.** **20** (22), pp. 24429–24443, 2012. doi:10.1364/OE.20.024429
7. V. Bagini, F. Frezza, M. Santarsiero, G. Schettini, and G. Schirripa Spagnolo, *Generalized Bessel-Gauss beams*, **J. Mod. Opt.** **43** (6), pp. 1155–1166, 1996. doi:10.1080/09500349608232794
8. A. R. Al-Rashed and B. E. A Saleh, *Decentered Gaussian beams*, **Appl. Opt.** **34** (30), pp. 6819–6825, 1995. doi:10.1364/AO.34.006819