# Broadband second harmonic generation in holey optical fibers

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Holey fibers are shown to have an ideal geometry for efficient parametric processes due to their tailorable mode area and dispersive properties. These fibers can have the additional advantage of single-mode operation at all the interacting wavelengths. We demonstrate theoretically that by appropriate choice of holey fiber geometry, these fibers can be up to four orders of magnitude more efficient for second harmonic generation than conventional poled optical fibers.

Holey or microstructured optical fibers posses wavelength-scale air holes in the cladding which lead to a unique range of optical properties. For example, the mode area can be tailored over three orders of magnitude,[1] and when the holes are small, these fibers can be endlessly single-mode.[2] A range of useful dispersion regimes have also been identified in holey fiber (HF). The zero dispersion wavelength can be shifted as low as 550nm,[1, 3] which period is $\mathcal{P}$. Expansion (2) shows that while QPM allows phase matching to lowest order, dispersive effects at higher orders contribute to phase mismatch between fundamental and second harmonic waves.

It can be shown that the efficiency of SHG ($\eta$) is

$$\eta \propto \frac{L^2}{A_{ovl}} sinc^2 \left(\frac{\Delta\beta L}{2}\right), \tag{3}$$

[7] when the nonlinearity is assumed to be uniform in the transverse plane, $L$ is the interaction length and $A_{ovl}$ is the effective area which takes account of the overlap between interacting waves:

$$A_{ovl} = \left| \int\int E_{SH}^{*} E_{F}^{2} dx\, dy \right|^{-2} \tag{4}$$

where $E_{SH}$,$E_F$ are normalised second harmonic and fundamental transverse modes. Although Eq. (3) is only strictly true for low-conversion efficiency processes and, for QPM, uniformly periodic structures, it gives a qualitative description. The efficiency is maximised for wavelengths which satisfy the QPM condition. We can define a bandwidth (BW) for the process as the wavelength range over which $sinc^2(\Delta\beta L/2) \geq 1/2$. Clearly a longer $L$ improves $\eta$, while narrowing the usable BW. For many practical applications it is desirable to maximise the BW without compromising the efficiency. Large bandwidth is important to ensure stable device operation or for devices operating in the pulsed regime when interactions must occur for all the spectral components of the pulse.

Efficient QPM-SHG and PDC have been demonstrated in periodically poled ferroelectric waveguides [8] and glass fibers.[7] Although high efficiency was achieved, the practical application of SHG is limited by the bandwidth and the lack of single mode operation at all wavelengths. For QPM-PDC (and difference frequency generation) complex waveguide on the relative group velocity, group velocity dispersion, dispersion slope, etc., at each wavelength. The dispersive properties of small-core HFs shown in Table 1 are critically dependent on the cladding geometry. As an example, although the material dispersion dominates at $0.775\,\mu$m resulting in net normal dispersion, both normal and anomalous dispersion are possible at $1.55\,\mu$m. Hence the BW is similarly sensitive to the fiber parameters, and indeed Table 1 shows that the BW can be tailored by a factor of 60. We find that the SH BW in holey fibers can be at least thirty times broader than in comparable conventional fibers (Table 2).

Another way of improving the SH efficiency $\eta$ is to reduce $A_{ovl}$, which is an effective mode area, which also accounts for the overlap between fundamental and second harmonic modes. Not surprisingly, $A_{ovl}$ is less sensitive to the geometry than the bandwidth is. The value of $A_{ovl}$ can be reduced in ways: the most obvious way is to reduce the core size, and Table 1 shows that smaller cores typically have lower $A_{ovl}$. In addition, the overlap between fundamental and second harmonic modes can be optimized. In particular, note with reference to Eq. (4) that ideally the second harmonic modal field should have the same mode shape/size as the square of the fundamental modal field in order to maximize this overlap, and hence reduce $A_{ovl}$. Both effects can be seen in Fig. 2, in which the fundamental and second harmonic modes of fibers **I** and **J** from Table 1 are superimposed on the fiber profiles. The larger holes in **J** confine the modes more tightly to the core, resulting in small modes and improved modal overlap. The contribution of the mode area and overlap factors to $A_{ovl}$ has been separated in Table 1, and we conclude that for the fibers considered here, the most significant contribution to efficiency results from the reduced mode size.

Although $A_{ovl}$ can be optimized using large air holes, this does not necessarily lead to the which allows for flexible device design. These examples serve to demonstrate the advantages holey fibers can offer over conventional technology.

Recently we have demonstrated experimentally that holey fibers can be poled. [10] Second harmonic generation was observed, and an electo-optic coefficient of $\approx 0.02pm/V$ was measured. Although these results could be improved substantially using the kind of holey fiber design described herein, they demonstrate that the complex air:glass geometry in a holey fiber is compatible with thermal poling techniques. Since holey fibers are generally fabricated by stacking tubes, it is straightforward to integrate the metal poling electrodes within large capillaries in the cladding region. This should allow for efficient poling, as the electrodes could be located close to the fiber core. Table 1 shows that these HFs require QPM periods ($\mathcal{P}$) ranging from $28 \rightarrow 67\,\mu$m, and that the best figures of merit have $30 < \mathcal{P} < 49\,\mu$m. These QPM periods are large enough to be easily produced, and so we anticipate that these fiber designs should be practical for QPM.

In conclusion, we predict that by using a holey or microstructured optical fiber, the efficiency of phase-matching can be improved for a range of nonlinear interactions including second-harmonic generation. As well as offering endless single-mode guidance, the dispersion, mode size and modal overlap can be optimized to improve the efficiency and usefulness of the SHG process. Combining these factors, we demonstrate that holey fibers can offer up to four orders of magnitude improvements for SHG over conventional fiber designs. Future investigations into other air hole arrangements are likely to yield further improvements to SHG efficiency, and similar improvements should also be possible for parametric processes other than SHG and PDC.

Fig. 1. Holey fiber with $d_{in}/\Lambda = 0.2$, $d_{out}/\Lambda = 0.1$

Fig. 2. Mode at $0.775\,\mu$m (left), mode at $1.55\,\mu$m (right) for Fiber "I" (top), Fiber "J" (bottom). Contours are seperated by 2 dB.

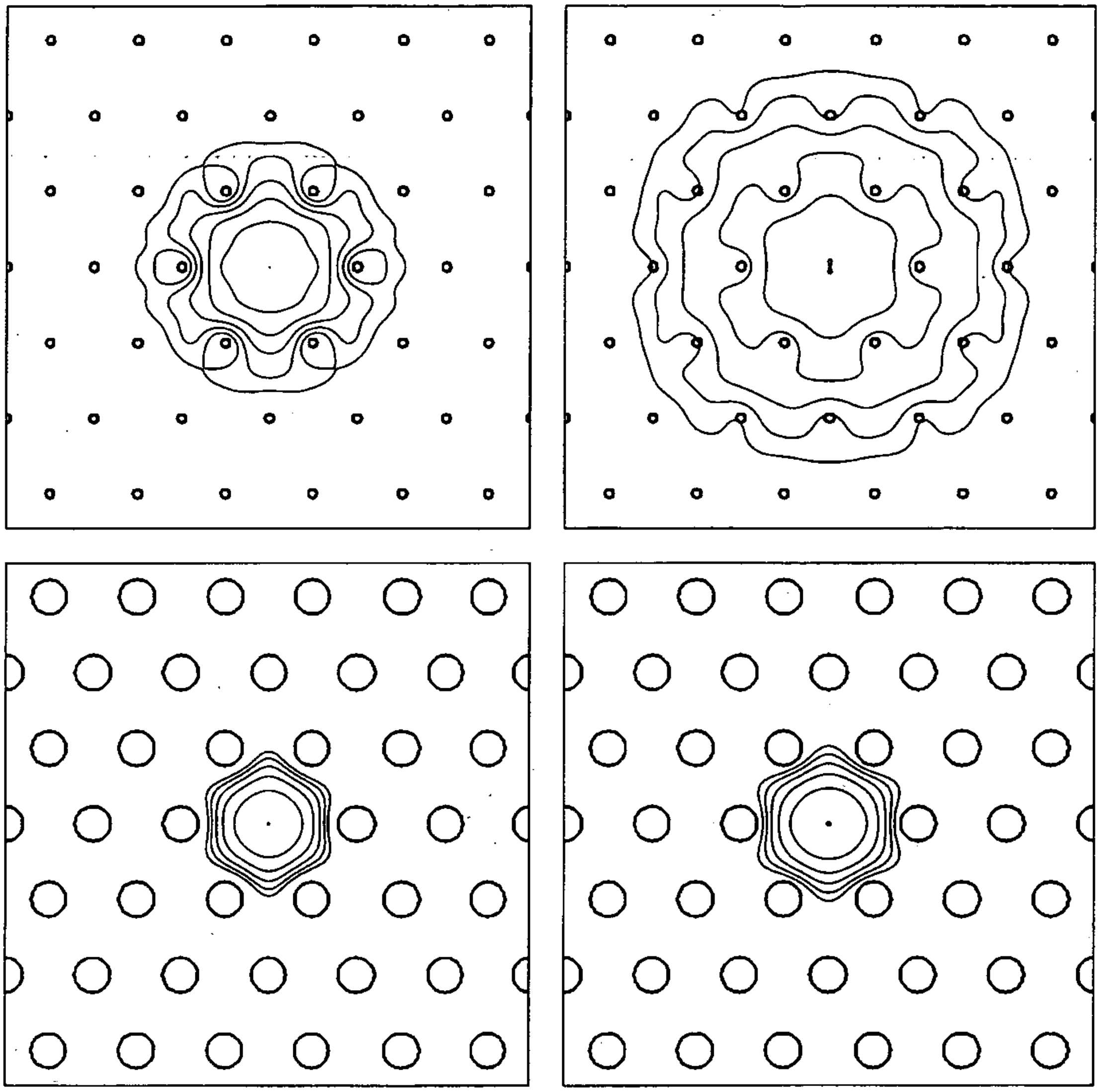

Figure 2. Monro et al. Optics Letters

Table 2. Properties and figure of merit for SHG in some conventional fibers (L=10cm device, $a$ is the core radius).

| | NA | $a$ | $A_{ovl}$ | BW | FOM |
|---|---|---|---|---|---|
| | | [$\mu$m] | [$\mu m^2$] | [nm] | [$\times 10^{-6}$] |
| **X** | 0.065 | 290 | 220 | 1.8 | 0.02 |
| **Y** | 0.19 | 36 | 35 | 2.0 | 0.1 |
| **Z** | 0.32 | 1.8 | 13 | 2.2 | 0.4 |