# Enhanced Efficiency of Second Harmonic Generation with Twelve-fold Photonic Quasi-crystal Fiber in Telecommunication Band

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**Abstract**— We design an index guided silica core photonic quasi-crystal fiber of twelve-fold symmetry for enhancing the efficiency of second harmonic generation by using the fundamental input wavelength of 1.55 µm in the telecommunication band. With the available poling technology, we optimize the pitch of the photonic quasi-crystal fiber at 7 µm and report a relative efficiency of second harmonic generation as $38.22\%\mathrm{W}^{-1}\mathrm{cm}^{-2}$ when the overlap area is $2.74\,\mu\mathrm{m}^2$ and phase-mismatch factor is $0.102\,\mu\mathrm{m}^{-1}$.

## 1. INTRODUCTION

Second harmonic generation (SHG) in telecom band is reported by many recent works which are helpful for the characterization of ultrashort pulses [1]. Enhancing the efficiency of SHG using photonic crystal fibers (PCFs) is also reported [2]. We recently analyzed the role of photonic quasi-crystal fibers in enhancing the efficiency and bandwidth of SHG [3, 4]. PQF, unlike PCF, has no translational symmetry. The lattice of cladding holes in PQF follows only rotational or mirror symmetry [5]. This structural modification in PQF helps in bringing the desired properties such as low confinement loss, endlessly single mode nature etc to a larger degree. Moreover, the circular nature of air hole distribution in the cladding of PQF increases the tight confinement of light in the core and hence increases the possibility of decreasing overlap area between fundamental and second harmonic. The quasi periodic arrangement of holes in the cladding does highly influence the modal confinement as well as the intensity distribution of both the fundamental and second harmonic fields inside the core. As a result, the two most important aspects of second harmonic generation, namely, phase mismatch factor and overlap area related to the efficiency of second harmonic generation get highly affected. Moreover, these two quantities must be as minimum as possible for enhancing the efficiency of second harmonic generation. Hence, in this study, we emphasize on minimizing these two factors with proper choice of geometrical parameters of the PQF. In [3, 4], we have used 1.06 m wavelength as input fundamental wavelength for SHG. Owing to the importance of SHG in telecommunication band, in this work, we analyze the efficiency of SHG from 1.55 µm fundamental wavelength with twelve-fold photonic quasi-crystal fiber (PQF).

## 2. SHG THEORY

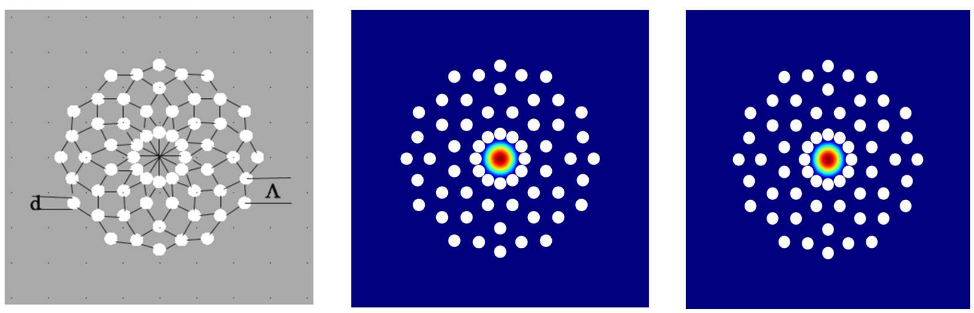
The efficiency of second harmonic generation is expressed as,

$$\eta = \frac{P_{2\omega}}{P_\omega} = P_\omega l^2 \frac{(d_{\mathit{eff}})^2}{A_{ovl}} \operatorname{sinc}^2\left(\frac{\Delta\beta l}{2}\right) \frac{8\pi^2}{\lambda_f^2 n_f^2 n_{sh} \epsilon_0 c} \tag{1}$$

Here $P_\omega$ is the fundamental power, $P_{2\omega}$ is the second harmonic power $l$ is the length of the fiber, $d_{\mathit{eff}}(=\chi^{(2)}/2\pi)$ is the non-linearity factor associated with second order susceptibility, $\chi^{(2)}$ [2–4]. $A_{ovl}$ is the overlap area of interaction between fundamental and second harmonic waves and the same is given by, $A_{ovl} = 1/I_{ovl}^2 = |\iint E_{sh}^* E_f^2 dxdy|^{-2}$ where $I_{ovl}$ is the overlap integral factor and $E_f$ and $E_{sh}$ are the normalized electric field intensities of fundamental and second harmonic waves, respectively. $\Delta\beta$ is the phase mismatch factor between fundamental and second harmonic, $\lambda_f$ is the fundamental wavelength, $n_f$ and $n_{sh}$ are the refractive indices of fundamental and second harmonic waves, respectively and $c$ is the velocity of light. For a poled fiber, the quasi-phase matching (QPM) technique is essential for the required phase-matching between fundamental and second harmonic. For an ideal QPM of 1st order, the phase mismatch factor is, $\Delta\beta = \Delta\beta' - l_{qpm} = 0$, where $\Delta\beta' = 2\beta_1 - \beta_2$, is the wave-vector mismatch between fundamental ($\beta_1$) and second harmonic ($\beta_2$) wave-vectors, respectively and $l_{qpm}$ ($=2\pi/\Delta\beta'$) is the QPM grating period. Longer QPM period helps in easier fabrication process in terms of altering the poling voltage over a sample periodically.

## 3. PQF DESIGN

The design of the twelve-fold PQF is shown in Fig. 1(a). In Fig. 1(a), the gray region signifies silica while the white holes represent air holes. Here we use Penrose type tiling with square and thin and thick types of rhombi for arrangement of air hole unit cells in the cladding [4, 5]. Here the lattice constant or pitch, $\Lambda$, is varied from 1 to 15 µm for the analysis. The upper limit of pitch is considered for low effective mode area and lower limit of pitch is considered for tight confinement of modes of both fundamental and second harmonic. The relative air hole diameter, $d/\Lambda$, is fixed at 0.5 by considering single mode propagation requirement [5]. Also we already reported the best overlap area can be achieved by PQF is at relative hole diameter 0.5 [3, 4]. Figs. 1(b) and (c) show the tight modal confinement of fundamental and second harmonic, respectively, for a pitch of 7 µm and a fiber length of 10 cm. From Figs. 1(b)and (c), we observe that the modal distribution of second harmonic approaches that of the fundamental. This can highly reduce the overlap area of SHG. Also due to the presence of 12 air holes in the first ring of the cladding, both the fundamental and second harmonic modes are tightly confined to the core and also become circular.




(a) (b) (c)

Figure 1: (a) The geometrical structure of the proposed PQF, (b) confinement of fundamental mode, (c) confinement of second harmonic mode.

## 4. SHG ANALYSIS

The Fig. 2 shows the variation of phase mismatch factor and overlap area with respect to pitch. Here we observe that, when pitch increases, the phase-mismatch factor decreases but the overlap area increases. Here we consider the quasi-phase matching (QPM) of first order for phase matching between fundamental and second harmonic. Hence the efficiency of SHG gets affected mainly with

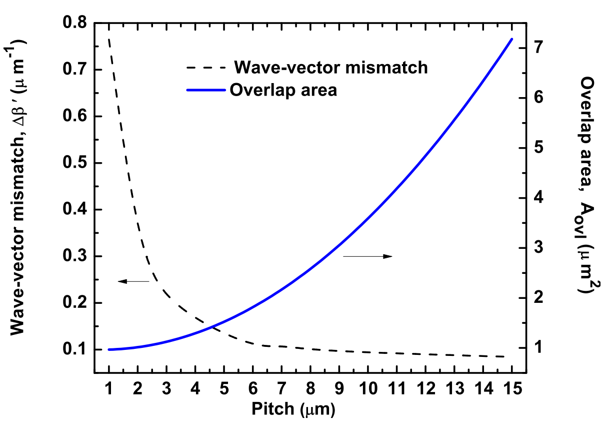



Figure 2: Variation of phase-mismatch factor and overlap area with respect to pitch.

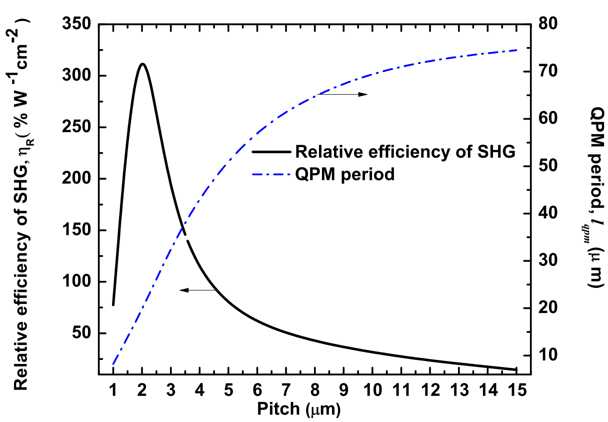



Figure 3: Variation of relative efficiency and QPM period with pitch.

the variation in overlap lap area. We point out that lowering the wave-vector mismatch parameter helps to get high QPM length and thus poling process becomes easier.

Having computed all the hitherto discussed physical parameters, we compute the relative efficiency ($\eta_R$) of SHG which is defined as, $\eta_R = \frac{\eta}{P_\omega l^2}$.

The Fig. 3 shows the variation of relative efficiency of SHG as well as the QPM length with variation of pitch. Here we find the efficiency increases with decrease in pitch where as the QPM length increases with increase in pitch.

In order to meet the poling requirements in PCF, we optimize the pitch value to be 7 μm and all the results presented in this work reflect for this pitch [6]. Hence at this pitch we report a relative efficiency of 38.22%$\mathrm{W}^{-1}\mathrm{cm}^{-2}$ where the QPM period is of 61.59 μm. In Table 1, we compare the SHG efficiency and QPM length with already reported values of PCF in [2].

Table 1: Comparison of relative efficiency and QPM length between proposed PQF and PCF reported in [2]

| Medium | $\eta_R$ (%$\mathrm{W}^{-1}\mathrm{cm}^{-2}$) | QPM length μm |
|---|---|---|
| PCF [2] | 3.71 | 29.10 |
| proposed PQF | 33.22 | 61.59 |

In Table 1, we find that the proposed PQF exhibits a very high relative efficiency as well as QPM length when compared with the PCF reported in [2].

## 5. CONCLUSION

We have designed the twelve-fold PQF for enhancing the efficiency of second harmonic generation of 1.55 μm of telecommunication band. For an optimum pitch of 7 μm, we report a relative efficiency of 38.22%$\mathrm{W}^{-1}\mathrm{cm}^{-2}$. We are enormously optimistic that with development of poling technique, the efficiency at the lower pitches of the twelve-fold PQF can also be obtained. In future, this work may be extended for higher harmonic generation of 1.55 μm.

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