Enhancement of Fundamental Mode Third Harmonic Generation Efficiency in Microfibres

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Abstract: We present a scheme to generate the third harmonic in the fundamental mode using microfibres, by introducing a counter-propagating pump field to partly compensate the phase mismatch and thus enhance the harmonic conversion efficiency.

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1. Introduction

Third harmonic generation (THG) remains an important area of research, with numerous applications. For example, with high-power laser drivers, such as the Omega Facility in Rochester University, USA and Shenguang II Facility at the Shanghai Institute of Optics and Fine Mechanics, China, THG is used to convert an infra-red pump into ultra-violet wavelengths, as the latter have a higher energy coupling efficiency in laser-plasma interactions. The systems for THG utilizing crystals are usually complicated because many optical components are required. In recent years however, harmonic generation in microfibres has been reported [1], thus opening the possibility for an all-fibre system for THG as a more robust alternative to the existing nonlinear-crystal technologies.

As with other nonlinear harmonic conversion processes, phase matching should be satisfied to attain efficient THG in microfibres. However, because of material and waveguide dispersion, only intermodal phase matching can be achieved directly in glass microfibres (i.e. between the fundamental pump mode and a higher order harmonic mode [2, 3]) and no efforts on generating the fundamental third harmonic mode in microfibres have been reported to date. Nonetheless, a fundamental mode output is often desired when developing a laser, because its nearly Gaussian field distributions would be easily compatible with other laser sources and equipment, and better for irradiation smoothing. In this paper, we therefore present a scheme in which the phase mismatch is partly compensated by introducing a counter-propagating pump field into the microfibre, thereby allowing the harmonic to be generated in the fundamental mode.

2. Basic principles

In the process of THG, the total electric field can be represented as a sum of the mode fields at each frequency ω_j

$$\mathbf{E}(x, y, z, t) = \sum \mathbf{E}_j(x, y, z, t) = \sum A_j(z) \mathbf{F}_j(x, y) \exp[i(\beta_j z - \omega_j t)] + c.c., \quad (1)$$

where $j = 1$ for the pump and $j = 3$ for the third harmonic; $\mathbf{F}_j(x, y)$ are the electric mode field distributions and $A_j(z)$ are the amplitudes of the modes normalised to their powers, that is, $|A_j(z)|^2 = P_j(z)$. β_j are the propagation constants of the modes in the fibre defined as $\beta_j = (\omega_j/c)n_j^{eff}(\omega_j)$, and n_j^{eff} are the effective indices of the modes.

In step-index glass-air circular fibres, the following coupled-mode equations can be used to describe the THG process [1],

$$\frac{\partial A_1}{\partial z} = in^{(2)}k_1 [(J_1|A_1|^2 + 2J_2|A_3|^2)A_1 + J_3A_1^*A_3 \exp(i\delta\beta z)], \quad (2a)$$

$$\frac{\partial A_3}{\partial z} = in^{(2)}k_1 [(6J_2|A_1|^2 + 3J_5|A_3|^2)A_3 + J_3^*A_1^3 \exp(-i\delta\beta z)], \quad (2b)$$

where $\delta\beta = \beta_3 - 3\beta_1$ is the phase mismatch, $k_1 = \omega_1/c = 2\pi/\lambda_1$ is the propagation constant of the pump in vacuum, $n^{(2)}$ is the nonlinear refractive index coefficient, and J_i are nonlinear overlap integrals (given in detail in Ref. [1]).

Fig. 1 shows the effective index curves for the fundamental pump mode $\text{HE}_{11}(\omega_1)$ and fundamental third harmonic mode $\text{HE}_{11}(3\omega_1)$ in a silica microfibre for $\lambda_1 = 1.55\mu\text{m}$. At the microfibre diameter of 550 nm where $n_1^{eff} = 1.012$ and

$n_3^{eff} = 1.334$, the phase mismatch is $\delta\beta = 3.9 \times 10^6 \text{m}^{-1}$. As this phase mismatch is large (comparable to k_1), the term $\exp(-i\delta\beta z)$ in Eq.(2b) oscillates very fast and prevents the fundamental mode harmonic from growing. Thus, efficient THG between the fundamental mode of the pump and the fundamental mode of the harmonic would be impossible without employing special methods to overcome such a large phase mismatch, as described next.

Fig. 1. Effective index curves for the fundamental pump mode $\text{HE}_{11}(\omega_1)$ (solid red) and the fundamental third harmonic mode $\text{HE}_{11}(3\omega_1)$ (dashed blue) in a silica microfiber for $\lambda_1 = 1.55 \mu\text{m}$.

If we introduce a weak counter-propagating light field [4, 5] at the fundamental frequency ω_1 into the fibre, the superposition of the forward-travelling and weak counter-propagating beams can be described by a forward-propagating field that is modulated in both amplitude and phase along the direction of propagation with a periodicity of half the laser wavelength [4], that is,

$$E_1(x, y, z, t) = A_{1t}(z)F_1(x, y)\exp[i(\beta_{1t}z - \omega_1 t)] + c.c., \quad (3)$$

where $\beta_{1t} = \beta_1 + \beta'(z)$, and $\beta'(z)$ has the form

$$\beta' = -\frac{2r\beta_1 \cos(2\beta_1 z) + 2r^2\beta_1}{1 + 2r \cos(2\beta_1 z) + r^2}. \quad (4)$$

Thus the actual total phase mismatch is $\delta\beta_t = \beta_3 - 3\beta_{1t} = \beta_3 - 3\beta_1 - 3\beta'(z)$ and hence $\beta'(z)$ acts as a compensative detuning which we can use to enhance the THG conversion. Importantly, the variation of $\beta'(z)$ along the propagation distance can be adjusted by changing the ratio of the backward-forward field amplitudes $r = A_1^-/A_1^+$.

3. Simulation results

Figure 2 shows the compensative and total detuning against propagating distance when the backward-forward amplitudes ratio is $r = 0.14$. The total detuning periodically approaches and even reaches zero, and at these positions, the harmonic power can be built up.

We calculate the third harmonic power in the presence of such a counter-propagating field by solving Eq.(2) numerically, and the results are given in Fig. 3. For small r , it is assumed that the counter-propagating pump generates a negligible counter-propagating harmonic signal. In the situation $r = 0$, i.e. with only the forward pump, the harmonic power remains very low, but when the counter-propagating field is introduced (though only with $r = 0.14$, or about 2% power of the forward pump) the harmonic power grows along the propagating direction, and in a microfiber tens of micrometres in length, the conversion efficiency obtains an enhancement of about one order of magnitude.

4. Conclusion

We have presented a scheme to enhance the fundamental-mode third harmonic generation efficiency in microfibres. By introducing an appropriate weak counter-propagating beam, the phase mismatch between the fundamental modes of the pump and third harmonic is partly compensated, enabling the harmonic power to grow along the propagation direction. This scheme offers an alternative idea for efficient harmonic generation by modifying the pump beam, and could potentially be applied to other small core waveguides such as wagon-wheel holey fibres or integrated waveguides.

Fig. 2. The compensative detuning $\beta'(z)$ introduced by the backward beam (black dashed curve) and the total detuning $\delta\beta_t$ (red solid curve) against propagating distance z , when the backward-forward amplitude ratio is $r = 0.14$.

Fig. 3. The third harmonic generation power against the propagating distance z . The pump power $P_0 = 1\text{ kW}$, nonlinear overlap integral $J_3 = 0.31\mu\text{m}^{-2}$, $\lambda_1 = 1.55\mu\text{m}$, and $n^{(2)} = 2.7 \times 10^{-20}\text{m}^2/\text{W}$.

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References

1. V. Grubsky and A. Savchenko, "Glass micro-fibers for efficient third harmonic generation," *Opt. Express* **13**, 6798–6806 (2005).
2. T. Lee, Y. Jung, C. A. Codemard, M. Ding, N. G. R. Broderick and G. Brambilla, "Broadband third harmonic generation in tapered silica fibres," *Opt. Express* **20**, 8503–8511 (2012).
3. T. Wu, Y. Sun, X. Shao, P. Shum and T. Huang, "Efficient phase-matched third harmonic generation in an asymmetric plasmonic slot waveguide," *Opt. Express* **22**, 18612–18624 (2014).
4. X. Zhang, A. L. Lytle, T. Popmintchev, X. Zhou, H. C. Kapteyn, M. M. Murnane and O. Cohen, "Quasi-phase-matching and quantum-path control of high-harmonic generation using counterpropagating light," *Nature Phys.* **3**, 270–275 (2007).
5. J. Peatross, S. Voronov and I. Prokopovich, "Selective zoning of high harmonic emission using counterpropagating light," *Opt. Express* **1**, 114–125 (1997).