SHG at the DBE

*Results of simulations and some observations*

Under the undepleted pump approximation, the conversion efficiency for second harmonic generation in a system that is homogeneous in the propagation (longitudinal) direction, such as a bulk material or a waveguide, may be conveniently defined as follows:

Where is the interaction length in the propagation direction (nonlinear interaction length), is the pump power at the input of the waveguide and ), is the second-harmonic power at the output of the waveguide. This definition of efficiency depends mainly on the following parameters: material nonlinearity, , overlap integral between fundamental and second-harmonic field, and phase-matching. Instead, the dependency on the input pump power and the interaction length is removed from this definition of efficiency, at least in the undepleted pump approximation. The units of , in the case of a 1D-confined waveguide are , since the power units are .

An approximated expression of the efficiency can be written for the waveguide under investigation:

In this expression, is the wavevector mismatch between the fundamental and the second-harmonic field, is the fundamental-frequency wavelength, and are the effective indices of the waveguide modes carrying the fundamental and the second-harmonic signals, respectively, and the nonlinear overlap integral quantifies the effective nonlinear susceptibility of the system:

We now proceed with the calculation of an estimated value of the efficiency, using the following assumptions: modal phase-matching between the interacting modes, i.e., , optimized overlap integral, i.e., , where is the geometrical cross-section of the waveguide. For an AlGaAs waveguide with core cross-section of a few hundred nanometers, it is reasonable to assume effective indices , and therefore the efficiency is .

We performed numerical simulations of second-harmonic generation in a phase-matched AlGaAs waveguide and indeed the efficiency value that we found is very close to the predicted one.

As an example, here we report the results for a homogeneous waveguide system, consisting of two cores of AlGaAs with thickness 200 nm, separated by a gap of 200 nm, embedded in a cladding of oxide. In particular we consider two cases: the phase-mismatched scenario that can be obtained using the actual data of the AlGaAs refractive indices and a phase-matched scenario obtained when the AlGaAs chromatic dispersion is properly modified in order to reach the condition . In both cases the efficiency is of order . In the mis-matched case, it is not useful considering waveguide lengths larger than one coherence length (), where the first maximum of conversion efficiency is reached. Under phase-matching, the SH intensity grows as L^2 as reported in Fig. xxx (d). Although here the phase-matching is reached by modifying the AlGaAs chromatic dispersion and therefore it is not a realistic scenario, there are modal phase matching techniques, based on the engineering of the modal dispersion by properly designing the waveguide cross section and selecting different modes for the fundamental and SH, able to provide phase-matching conditions of SHG similar to those reported in Fig. xxx (c) and (d).

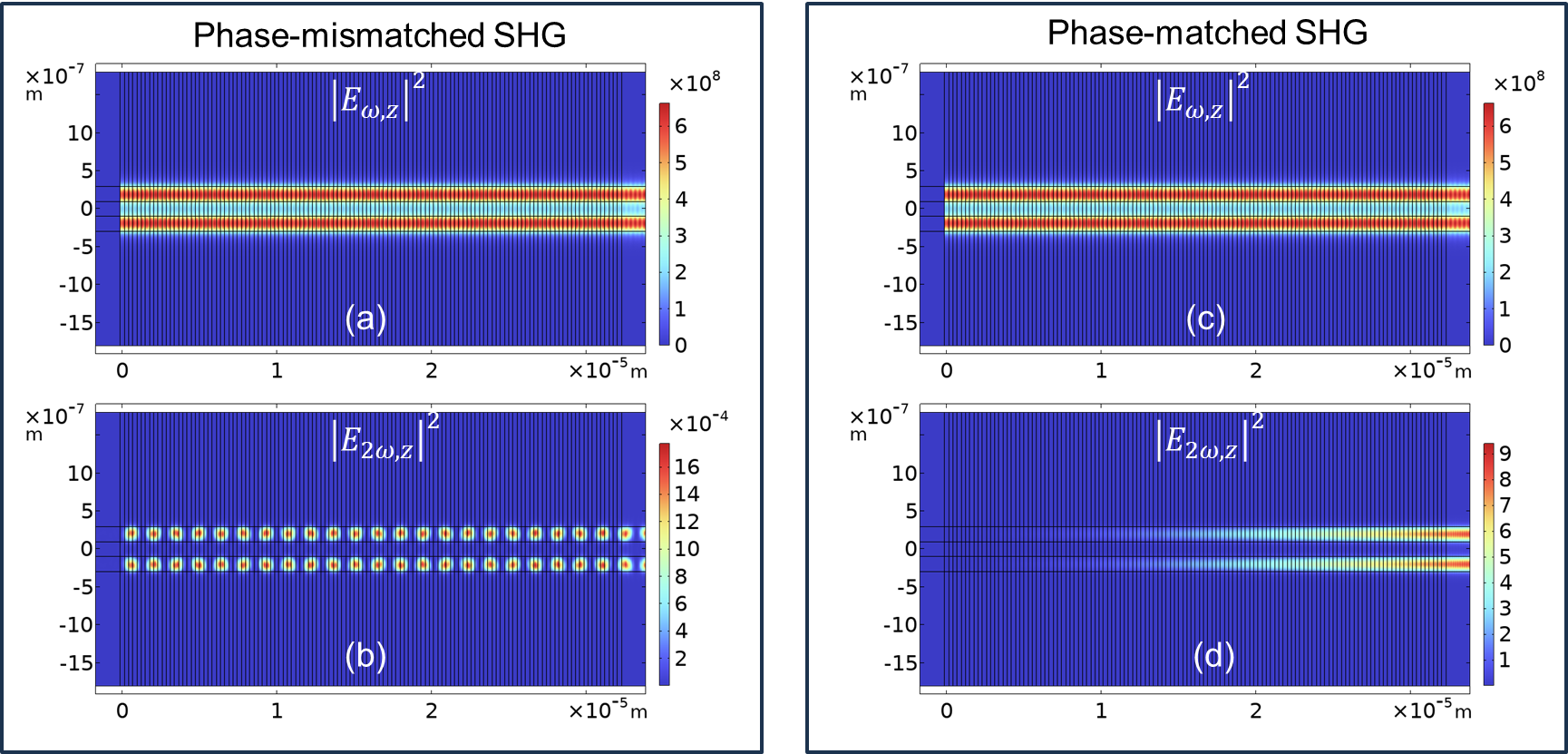


Fig. xxx. SHG from a homogeneous waveguide with 1d confinement. The cross section of the waveguide is made of two cores of AlGaAs, separated by a gap. In (a) and (b) we report the field intensity at the pump (a) and SH (b) using the actual dispersion data of the AlGaAs index (n=3.2837 at the fundamental wavelength and n=3.5607 at the SH wavelength): The dispersion of AlGaAs result in a phase-mismatched SHG process. . In (c) and (d) we report the field intensity at the pump (a) and SH (b) using a hypothetical AlGaAs-like material (n=3.2837 at the fundamental wavelength and n=2.975 at the SH wavelength), which allows phase-matching, i.e., fundamental and SH modes have the same effective index, resulting in a phase-matched SHG process.

It is well known that a inhomogeneous structure – a structure in which the optical properties vary in the propagation direct – may show second harmonic intensity that grows faster than . A noteworthy example are photonic crystals in which both the pump and the harmonic signals may be tuned at the edges of photonic band gaps. The enhancement in conversion efficiency with respect to homogeneous structures originates from the (longitudinal) distributed resonances for the interacting fields, which provide a field enhancement effect. Under resonance conditions, a correction factor in the expression of the overlap integral must be introduced, i.e. , which accounts for the quality factors of the resonances available at the fundamental and second-harmonic frequencies. Since the quality factor may increase with the length of the structure, the second harmonic power may grow more rapidly than .

The two key aspects to consider in the degenerate band edge system are: phase matching between fundamental and second-harmonic signals and quality factors at both the fundamental and second-harmonic frequencies.

We consider the following structure: waveguide widths 200nm, gap of 200nm, teeth widths of 214nm, periodicity 270nm, teeth shift equal to half the periodicity. The periodic structure shows a degenerate band gap at 191.2 THz, as shown in Fig. xxxx (left). While the Bloch modes at the FF are bound (eigenfrequencies are real), all the Bloch modes at the SH are leaky (complex eigenfrequencies) and therefore they radiate energy into the cladding. This is not an ideal condition for SHG, since, even though the intensity of the FF signal is boosted due to the band edge effect, and therefore the SH sources are highly intense, the radiation towards the waveguide structure (x direction) may be not efficient.

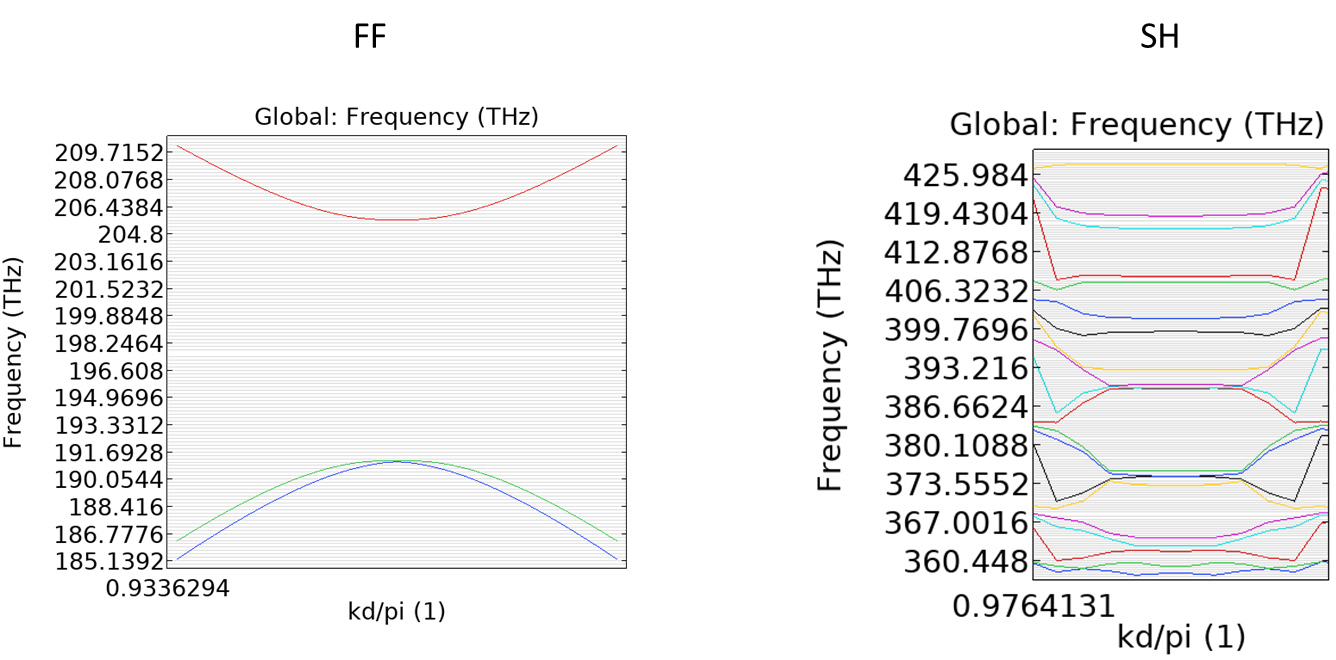


Fig. xxxx Dispersion diagram of the structure near the FF (left) and near the SH frequency (right).

We now consider a finite structure with 120 periods. The pump is coupled to one of the transverse modes of the structure at the input cross section, as illustrated in Fig. xxxxx. In particular we consider the mode that is mostly localized in the bottom waveguide.

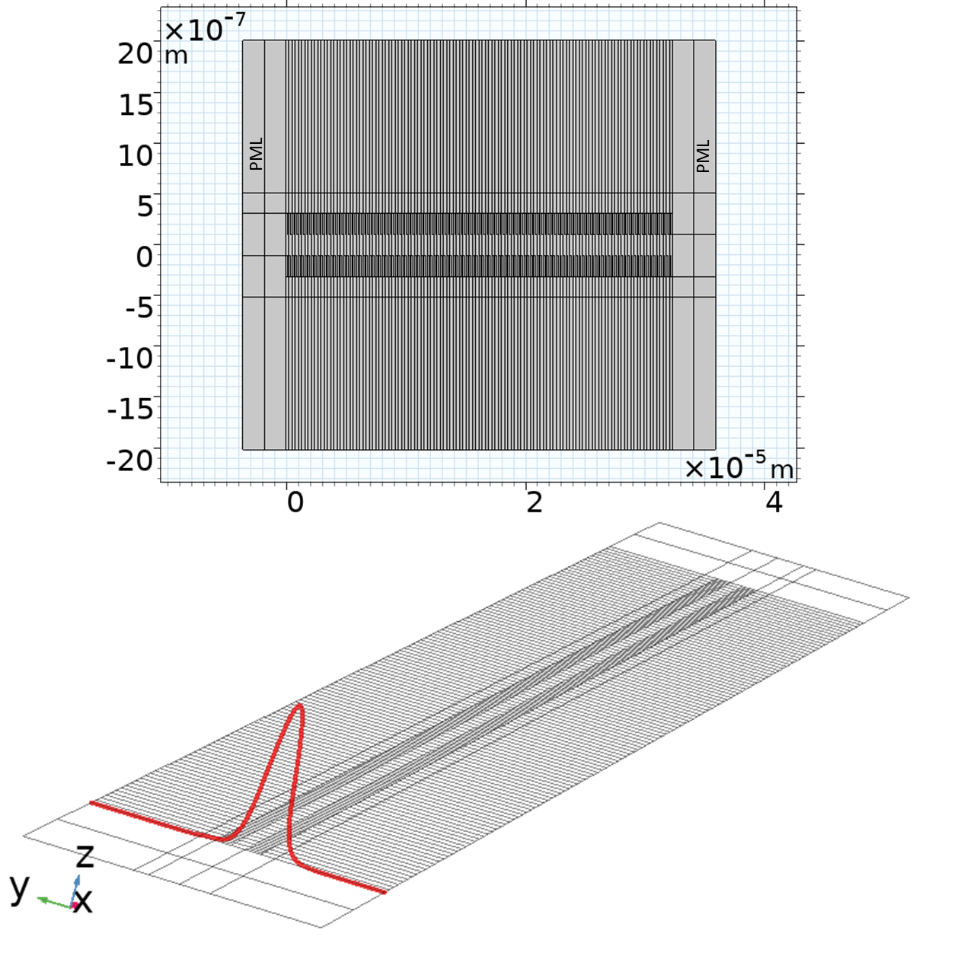


Fig. xxxxx Structure under investigation (above) and excitation (below)

First, we calculate the linear power transmission near the fundamental frequency of the expected band edge. The input power is 1 W and the transmission is calculated by integrating the Poynting vector of the FF field along the x direction (propagation direction). As shown in Fig. x6, the transmission shows a high-quality factor resonance centered at 191.2 THz (Q factor of approximately 6000), where the band edge of the Bloch dispersion diagram occurs, and a forbidden band above this frequency.

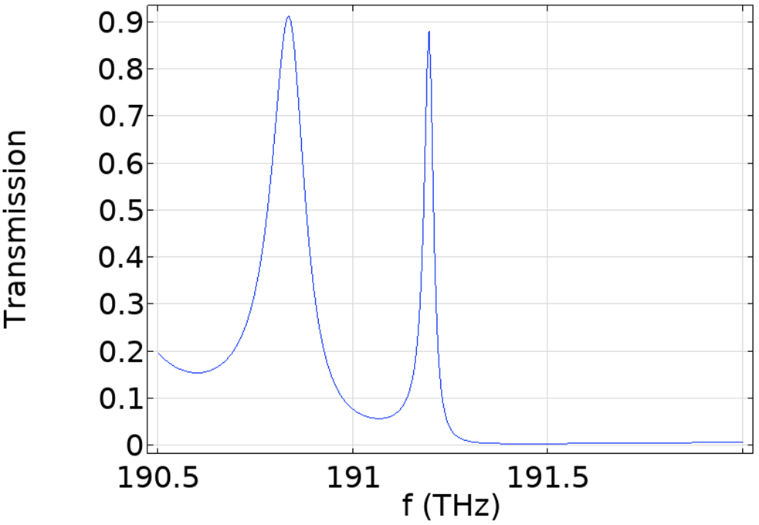


Fig. x6 Power transmission of the structure under investigation.

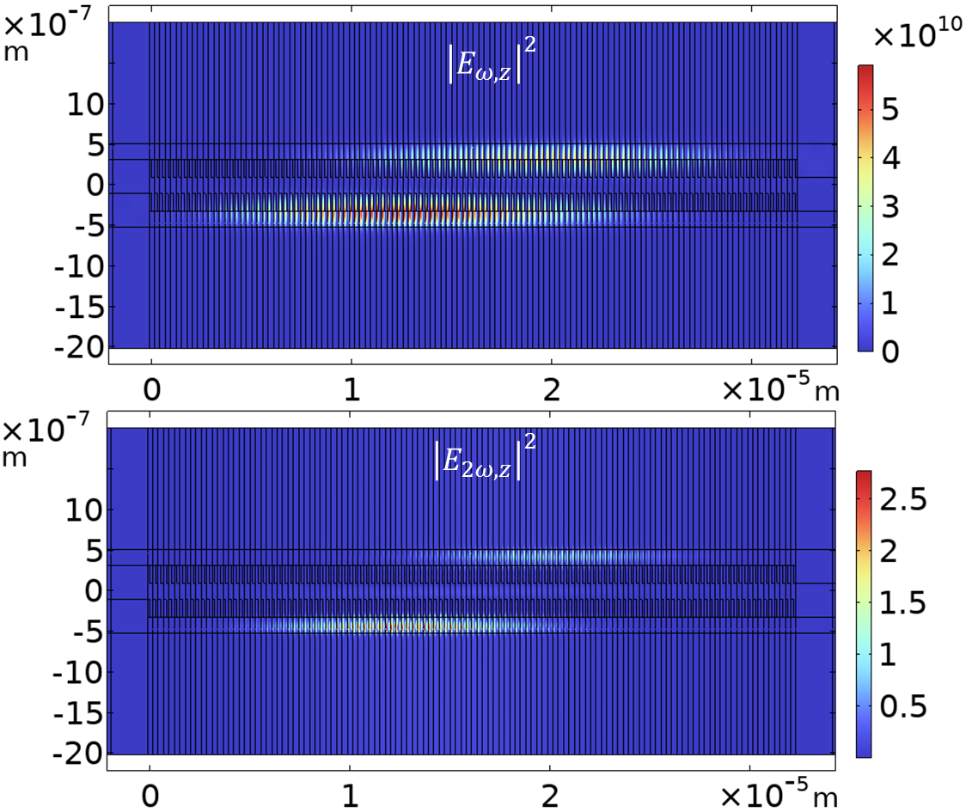


Fig. x7 FF and SH field intensity distribution

Even though the local SH field intensity distribution is larger than in the case of the straight (homogeneous) waveguide, the overall efficiency , measured by integrating the output SH power in transmission (along x, the propagation direction of the waveguide) is 3 orders of magnitude smaller, . A closer look at the field distribution shows that the structure is mostly emitted towards the cladding.

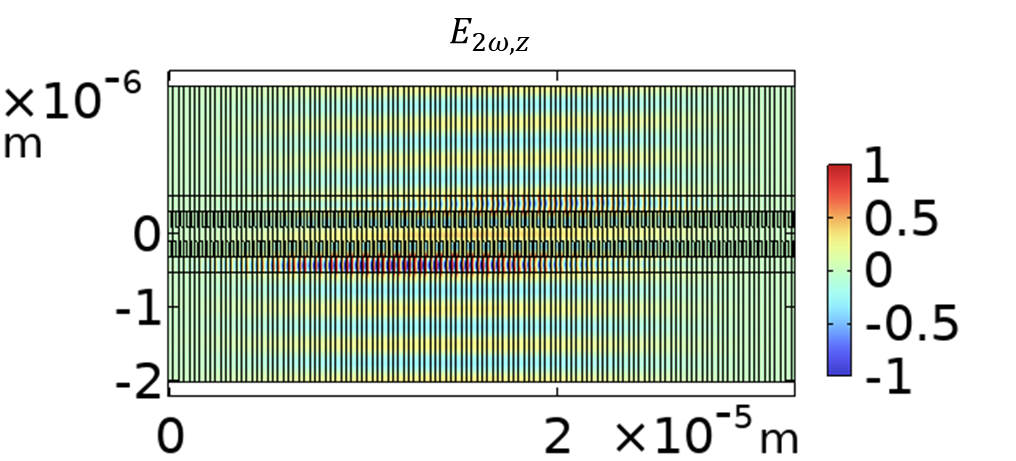


Fig. x8 SH field distribution

A careful engineering of the Bloch dispersion around the SH frequency may significantly boost the efficiency. To investigate this possibility we perform a parametric study of the conversion efficiency by tuning the index of the AlGaAs at the SH frequency, while the solution at the FF remains unaltered.

The efficiency as a function of the AlGaAs index at the SH frequency, reported in Fig. x9, clearly shows a strong enhancement near .

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Fig. x9 Conversion efficiency as a function of the index of AlGaAs at the SH

The field distribution at this efficiency peak is shown in Fig. x10. This strong enhancement is most probably due to a combination of DBE effect and modal phase matching.

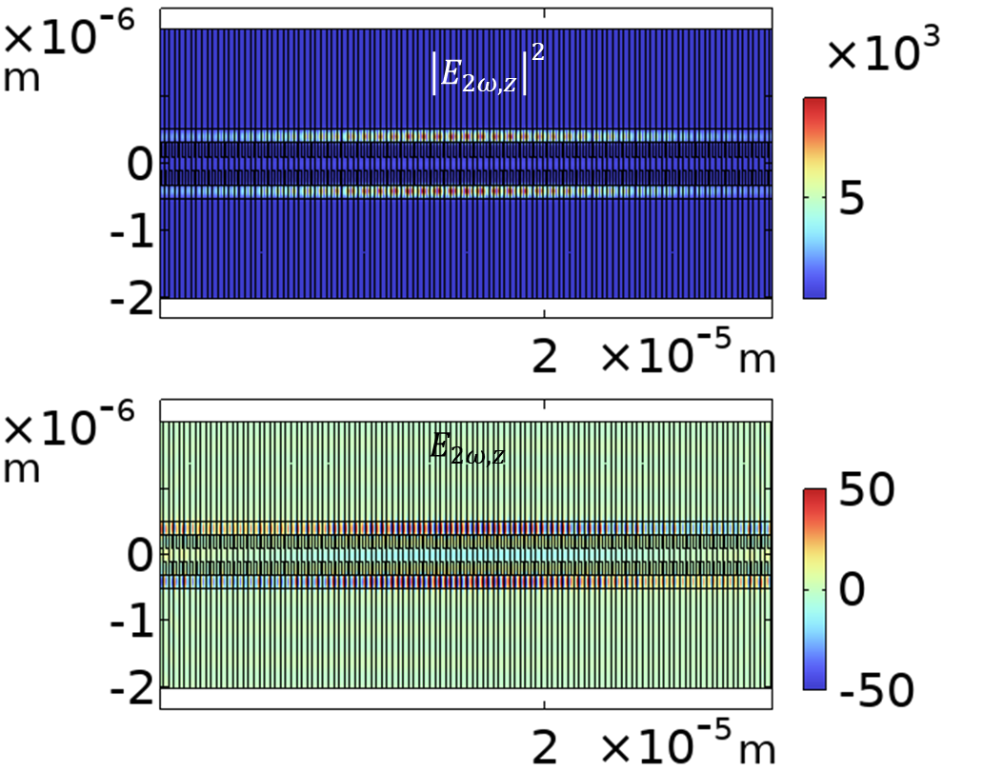


Fig. x10