

STSM REPORT

STSM Application number: COST-STSM-BM1205-34893

STSM Grantee: Mauro Fernandes Pereira

Early Stage Researcher ? NO

STSM title: Waveguide Effects in nonlinear generation of THz radiation in Superlattices

Home Institution: Sheffield Hallam University

Host Institution: Universidade do Porto

STSM period: 2016-09-10 to 2016-09-24

STSM purpose: The goal of this STSM was to investigate the possible influence of waveguide effects in the generation in the frequency multiplication of THz radiation after a GHz input in a semiconductor superlattice. Input for the calculations is obtained by means of a Nonequilibrium Green's Functions Approach that delivers the harmonic component. There is at a moment a discrepancy in the comparison between calculations without waveguiding and actual harmonic generation power delivered by experimental teams. This system is promising as both sources and detectors of THz radiation at room temperature that could be used for skin cancer detection.

Working Group: The research performed in this STSM fits best within WG3 – since the system considered for generation and detection of radiation reaches the THz range.

Description of the work carried out during the STSM: During this STSM we have investigated different approaches to extend the inclusion of waveguiding effects in superlattices used as frequency multipliers, extending the second harmonic generation of Ref. [1] to an arbitrary harmonic order.

Description of the main results obtained: The influence of waveguiding effects in the generation of arbitrary harmonics in a superlattice has been calculated. The results that the effects do not influence significantly the ratio of harmonic powers calculated with a hybrid Nonequilibrium Green's Functions and rate equation approach. The waveguide has a length L .

The average power emitted at the l^{th} harmonic to input frequency ω is found to be given by

$$P_{l\omega} = \frac{\mu_0 |j_l|^2 c}{8 \sqrt{n_{l\omega}'^2 + n_{l\omega}''^2}} \left| \frac{1 - e^{-L\kappa_{l\omega}''} e^{iL\Delta K_l}}{\Delta K_l + i\kappa_{l\omega}''} \right|^2$$

Where, j_l is calculated with a hybrid approach that combines input from Nonequilibrium Green's functions calculations to obtain the static (dc) voltage-current. The output parameters from the NGFT calculations are in turn used as input to a relaxation rate approximation that delivers analytical expressions for the harmonic current. The real and imaginary parts of the complex refractive index at frequency $l\omega$ and the mismatch in wavenumber are calculated and appear in the waveguiding factor above are

$$\mathcal{R}\{\kappa_{l\omega}\} = n_{l\omega} \frac{l\omega}{c},$$

$$\mathcal{I}\{\kappa_{l\omega}\} = \kappa''_{l\omega},$$

$$\Delta K_l = \mathcal{R}\{\kappa_{l\omega}\} - lk_{\omega}.$$

The relevant quantity is the ratio of emitted harmonic powers, since this can be directly computed with experiments. The most important conclusion is that the ratio of waveguiding factors plays a negligible role and the calculated rate of emitted power is dominated by the material term j_l , which we have calculated to be in excellent agreement with experimental findings from our colleagues in Nizhny Novogorod and which have three orders of magnitude reduction from the third to the 21st Harmonic, while the waveguiding factor remains essentially constant as seen in Fig. 1 below.

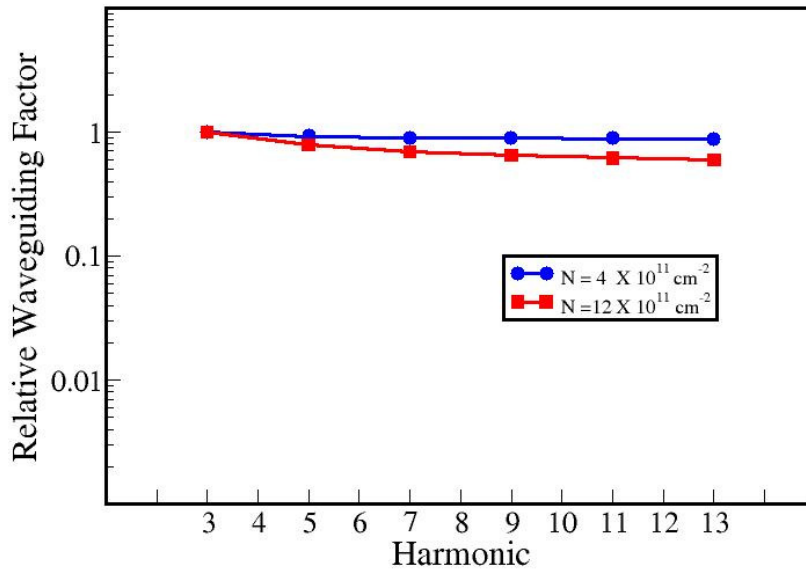


Fig.1 Ratio of Waveguiding Factor for high harmonics compared to the third harmonic. The superlattice absorption has been actually over estimated by considering multiple quantum wells of 10 nm width and a high doping density. The waveguide length is $L=2\mu\text{m}$.

Note that this results go far beyond those in Ref. 1 due to the following reasons: (i) The expression above is valid for any harmonic power, not just the second harmonic. (ii) The Green's Functions used in Ref. 1 is only valid for real $\kappa_{l\omega}$. The results shown here using the SVEA do not need to use it. (iii) Explicit calculations for $\kappa_{l\omega}$ and thus $n_{l\omega}$, while in Ref. 1 a value taken from a table found in the literature is used.

Mutual benefits for the Home and Host institutions: This research exposed the Host institution to the field of THz generation, detection and their applications and the Home institution benefited from different methods to deal with light propagation in waveguides.

Future collaboration with the Host institution (if applicable): One of the various possible topics for future cooperation is a more complete study of nonlinear propagation in the GHz-THz range in semiconductor superlattices.

Foreseen publications or conference presentations expected to result from the STSM (if applicable): An Optics express or Applied Optics publication discussing the derivation of waveguiding effects for high order harmonics generated by the superlattice is expected. The results may be otherwise included in a more complete paper under preparation describing nonlinear harmonics and a seminal contribution to the field of GHz nonlinear optics intended for submission to the NATURE SERIES.

Reference:

1. David O.Winge, Martin Lindskog, and AndreasWacker, Microscopic approach to second harmonic generation in quantum cascade lasers, Optics Express 22, 18930 (2014).



Visit of Professor Mauro Pereira to University of Porto **To the Grant Holder of the COST Action BM1205**

Porto, 26 September 2016

I hereby confirm that Prof. Mauro Pereira visited Physics Department, Universidade do Porto, during the period 10/09/2016 to 24/09/2016 . We had a very successful cooperation in which we have extended the study of nonlinear optics to semiconductor superlattices used as frequency multipliers and delivered equations that help estimate Waveguide Effects in nonlinear generation of THz radiation in Superlattices.

The method and numerical programs developed should lead to publications and to an impact in the ACTION, since we hope that our experimental colleagues will test the findings of our simulations.

Yours sincerely,


Augusto Rodrigues

STSM outcome form

STSM application number	Home institution & country	Host institution & country	BM1205 WG	Objective of the collaboration	Results of the collaboration
COST-STSM-BM1205-34893	Sheffield Hallam University, UK	Universidade do Porto, PT	WG3	Evaluate the influence of waveguiding effects in the generation of high order harmonics in superlattices.	As we have hoped the relative influence of waveguiding effects on the emitted harmonic powers in a superlattice has been found to be negligible compared to the material effects expressed by a NEGF calculation.

