# Time Domain Modeling of multimode selenide-chalcogenide glass fiber based mid infrared spontaneous emission sources

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## ABSTRACT

We develop time domain models of selenide-chalcogenide glass fiber based MIR spontaneous emission sources. The modeling parameters used are derived from experimentally obtained data. The models are based on the rate equations' approach to simulate the distribution of ions between the relevant energy levels. The optical power distribution within the fiber is calculated by solving a set of partial differential equations using specially developed finite difference schemes that allow for a direct inclusion of the step discontinuities appearing at the fiber facets. The results obtained allow for a thorough analysis of luminescence from lanthanide ion doped chalcogenide fibers.

Keywords: Mid infrared photonics, chalcogenide glass fibers, numerical modelling.

## **1. INTRODUCTION**

Chalcogenide glass fiber technology is intensively developed due to its numerous applications, which use mid-infrared (MIR) light. A key element in MIR applications is the MIR light source. Thus chalcogenide glass fiber technology has progressed significantly over the last years [1-12]. So far chalcogenide glass fibers have been used to realize with success Raman lasers [13], supercontinuum sources [14] and spontaneous emission sources (SES) [15]. In this contribution a particular focus is given to the numerical analysis of the optical properties of SES operating within the MIR part of the optical spectrum, which have found application in sensor technology [16]. The structure considered consists of a section of a chalcogenide glass fiber, which is doped with lanthanide trivalent ions (Fig.1). A pump light source is applied at one end of the fiber whilst MIR light is collected from the other end. Modeling of such structures is closely related to the fiber laser modeling of chalcogenide glass based fiber laser structures. This topic has been very intensely researched using steady state models [17-20]. Here a time domain technique is developed for the purpose of the analysis, and numerical simulations of the time dependence of photon fluxes and level populations are performed.

## 2. NUMERICAL MODELING

The structure studied is doped with trivalent terbium ions (Fig.2). The pump is operating at 2950 nm. The transition between levels 2 and 1 is assumed to be approximately non-radiative whilst the MIR light is generated by radiative transitions between levels 1 and 0, which is approximately centered at 5000 nm.

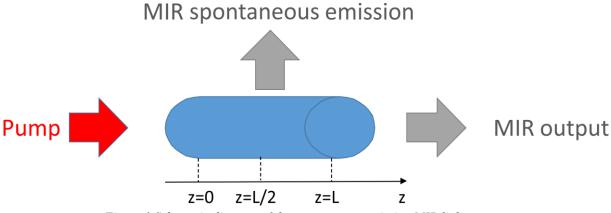


Figure 1.Schematic diagram of the spontaneous emission MIR light source.

The modeling algorithm applied, operates in three stages. In the first stage an initial guess is provided to a relaxation method steady state solver [21], which calculates a consistent solution at steady state for a given pump power. Then this solution is refined by the time domain model, which uses the method of lines [22] to refine the

initial steady state solution. This avoids the generation of numerical artefacts, which could result from a numerical mismatch between the steady state solution calculated by the relaxation method and the time domain model. The last stage of the algorithm performs the time domain analysis for a give shape of the pump temporal evolution.

Fig.3 shows a comparison between the spatial distributions of energy level populations and MIR and pump light within the fiber, which have been calculated by the algorithm at the first and second stage of the execution. The terbium ion concentration was  $9.51 \times 10^{24}$ /m<sup>3</sup>, the fiber length was 200 mm whilst the incident pump power was 100 mW. These results confirm a very good agreement between the results obtained by two different numerical techniques.

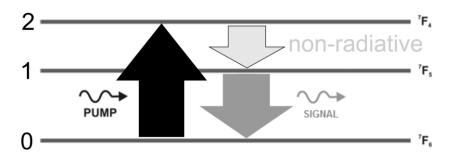


Figure 2. A schematic diagram of trivalent terbium ion energy levels.

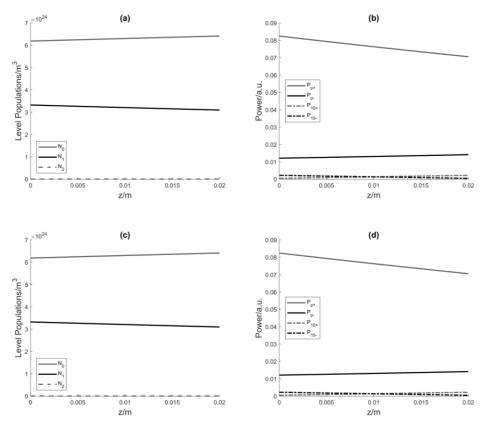


Figure 3. Spatial dependence of the level populations and power distributions calculated by the relaxation method (a) and (b), respectively, and the time domain method (c) and (d), respectively. The superscripts '+' and '- ' correspond to forward and backward propagating wave, respectively.

Fig.4 shows the dependence of energy level populations and signal and pump powers on the spatial and temporal dimensions. The pump power was switched off from a high level of 100 mW along a cosine square temporal waveform within 0.01 ms. The level 1 population at z = 0 (a) and z=L (b) follows a slow decay at a rate governed by the radiative lifetime of level 1. Since, the population of level 3 is near to zero the slow decay of level 1 population is reflected in the corresponding growth of the level 0 population. The pump power for the forward traveling wave at z = L and the backward traveling wave at z = 0 follows the shape of the switching of

cosine square waveform with a tiny delay resulting from the photon lifetime within the cavity (Fig.4c). The signal forward and backward traveling waves decay at a much slower rate, and follow the decay rate of the energy level 1 population. At the final simulation time equal to 100 ms a steady state is reached approximately, whereby almost all ions are in the ground state (Fig.4e). There is still small residual photon population within the cavity (Fig.4f) due to a relatively low decay time of 13.1 ms.

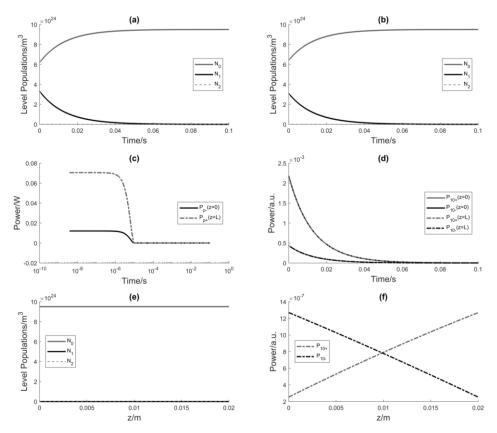


Figure 4. Spatial distribution and temporal dependence of level populations and power distributions calculated by the time domain model: (a) – energy level populations at z = 0, (b) – energy level populations at z = L, (c) – power temporal dependence, (d) – MIR signal temporal dependence, (e) – energy level distributions at 100 ms, (f) – MIR signal distribution at 100 ms. The superscripts '+' and '-' correspond to forward and backward propagating wave, respectively.

#### **3. CONCLUSIONS**

In the paper a time domain model of terbium ion doped selenide-chalcogenide glass fiber is used to model the time and spatial dependence of the energy level populations and photon densities. The results obtained give a detailed picture of the spatio-temporal dynamics of photons within the fiber and of the interactions between photons and ions.

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