Numerical Calculation of Active Waveguide Bragg Gratings Amplification Dependences

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A numerical study of active WBG is made in this work. First, a numerical method is implemented to consider the reflective behaviour of a Bragg grating written within an active Er^{3+}/Yb^{3+} doped waveguide. Second, the WBG response is analysed as a function of the grating properties and pumping conditions. A significant gain in the WBG reflected signal is obtained, which represents a promising result for potential active waveguide photonic applications.
Keywords: *waveguide Bragg grating, active waveguide, grating coupling coefficient, reflectivity*

INTRODUCTION

A distributed waveguide Bragg grating (WBG) consists of a periodic perturbation of the refractive index of the light guiding region inside a bulk material. The perturbations lead to an interference behaviour so that when a light wave enters the grating, some particular wavelengths can be efficiently reflected if they satisfy the Bragg condition [1,2]. This property can serve as the basis for many photonic devices such as optical band filters, optical sensors or external cavity lasers [1].

Besides, rare earths doped waveguides present an active character when light of a particular wavelength is guided, so that a light amplification can overcome the attenuation loses and therefore a power gain can be obtained [3,4]. The combination of both remarkable behaviours would be useful for potential photonic applications such as monolithic lasing and amplifying structures. However, it also represents a challenge to model and optimize its design and performance.

In this work, both aspects are addressed together as an initial approach. First, a numerical program has been developed to complementary simulate the active behaviour of an Er^{3+}/Yb^{3+} doped waveguide and the reflective characteristics of a distributed Bragg grating written within the waveguide. Second, a numerical study has been carried out in order to analyse the WBG gain capability and its dependences on the main grating parameters and working conditions. As a consequence, this work aims to be the basis for further theoretical-experimental studies that fully characterize and optimize the WBG response for potential active waveguide photonic applications.

METHODOLOGY

A numerical program has been implemented in order to simulate the light power propagation evolution within an active Er^{3+}/Yb^{3+} co-doped waveguide working at its maximum amplification wavelength (1534 nm) [4]. At the same time, a uniform Bragg grating structure written within the guiding core is simulated. In order to numerically simulate its response, the WBG is divided in N uniform sections and an iterative calculation is employed. The propagated power in each of these sections and its derivative are used by a Runge-Kutta method, so that their evolution along the waveguide propagation direction z can be determined. For this aim, the next equation is calculated by the program in each i section to determine the signal and pump power propagation:

$$\frac{dP_i(z)}{dz} = \left[A(\eta,\sigma,z) - \alpha + \frac{\ln(t_i)}{\Delta z}\right] P_i(z) \tag{1}$$

Three terms are distinguished within the brackets. The first one, A, represents a function which determines the waveguide active behaviour along the propagation direction depending on the overlapping factors between the mode intensity and population density distributions, η, and the levels transition cross section, σ. More details of this function can be found in [4]. The second term is the power attenuation constant of the media. The third term is included in order to consider the reflective characteristic of the uniform Bragg grating.

Consider a N-sections grating of total transmissivity T. Then, the transmission coefficient associated to every i-th Δz-length section, t_i, is related to the total grating transmissivity as $T = t_i^N$. Obviously, the t_i coefficient and Δz depend on the number of sections N in which the grating is divided. Nevertheless, in order to better understand the Bragg grating dependences and contribution to the active WBG response, the two main grating characteristics can be broken down and isolated. It is well known that the maximum passive WBG reflectivity is described by [2]:

$$R = \tanh^2(\kappa L) \tag{2}$$

where L is the grating length and κ its coupling coefficient (attenuation loss not considered). The grating coupling depends on many writing parameters (grating period, refractive index modulation amplitude, duty cycle, etc.) [1] which can be adequately selected at the WBG manufacturing process to optimize its properties [2]. However, this is not the specific aim of this work but the active WBG dependence on this parameter. Then, the t_i coefficient is related to both parameters since the grating transmissivity can be simply described by $T = 1 - R$.

Once all these considerations are implemented to the code, the copropagating power evolution along the z direction is calculated using equation (1) from the grating entrance towards its end. Then, the counterpropagating power is calculated backwards analogously. The adequate boundary conditions (injected signal and pump powers) at both grating ends are taken into account for these calculations. All this process is considered as a complete iteration. Then, both co- and counterpropagating powers are used as starting values for a new iteration, and a converged solution is achieved in typically 4-6 iterations, when the iterative process is interrupted. A previous study has been done to verify the adequate numerical program set-up: simple active waveguide ($t_i = 1$) and passive WBG responses have been checked [2,4]. In addition, the adequate number N of sections is properly selected to reach a compromise between minimal computational times and accurate calculation results.

RESULTS

Several simulations have been carried out to study the fundamental dependences of the WBG amplification properties. As an initial approach, two tuneable parameters in the WBG manufacturing process such as the grating's coupling coefficient and length are analysed. In addition, a fundamental working condition such as the pump power injected to the WBG to stimulate the amplification behaviour of the rare earth doped waveguide is also studied.

First, the reflectivity of a 5 mm WBG has been calculated as a function of the grating coupling constant. Three pump power conditions have been considered: 200 mW copropagating, 300 mW bidirectional and zero pumping. Simulations have been carried out using a signal wavelength of 1534 nm (100 µW signal power). The pumping wavelength used is 976 nm. An attenuation loss factor $\alpha = 0.03$ mm^{-1} has been considered, which represents a typical value for these media. The results of the WBG reflectivity are shown in Figure 1.

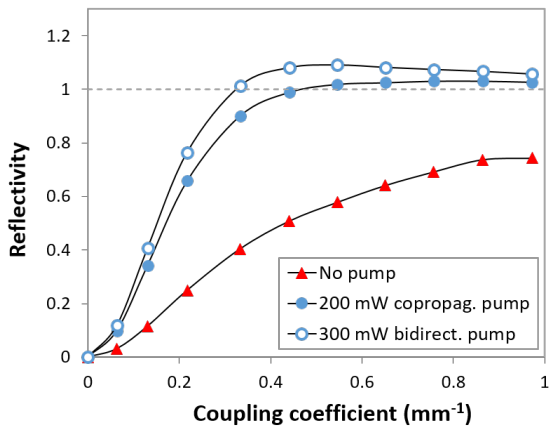

Fig. 1. Reflectivity of a 5 mm long WBG as a function of the grating coupling coefficient. Three pumping conditions are considered.

When pumping is not injected, the reflected signal is similar to that expected for a non-amplified Bragg grating. However, when the pump is considered, the reflectivity clearly increases. First, when only the copropagating pump is employed, the attenuation losses are balanced by the active waveguide behaviour even to obtain a reflected signal slightly greater than the one injected to the grating. Second, when a bidirectional pump is employed, a maximum gain of 9% is detected with grating coupling coefficients around $\kappa = 0.55$ mm^{-1}, which represents a considerable value to be manufactured [2]. Although the pump power in both cases is not exactly the same value,

it is observed that calculations lead to a saturation of the amplified response when coupling coefficients tends to 1 mm^{-1}, that is to say, when the grating is much more efficient. This result is consistent: the signal is more efficiently reflected and, therefore, less amplification can occur along the active waveguide. The same simulation has been carried out with two others grating lengths of 3 and 10 mm in order to study the relevance of this characteristic parameter. Results with copropagating and bidirectional pumping are shown in Figure 2.

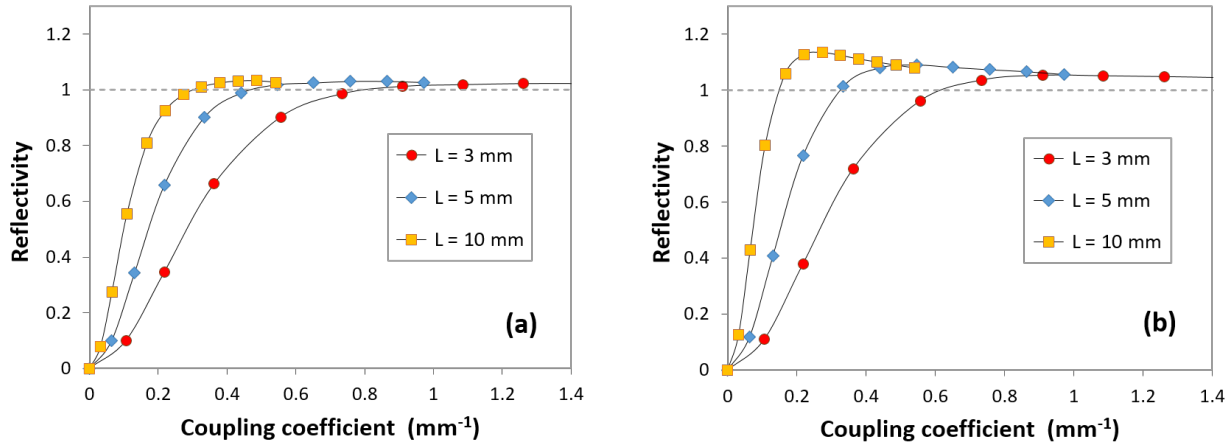

Fig. 2. Reflectivity obtained with WBG lengths of 3, 5 and 10 mm as a function of the grating coupling coefficient. Pumping conditions employed are (a) 200 mW copropagating pump power and (b) 300 mW bidirectional pump power.

Results using the copropagating pump, Figure 2(a), confirm the already mentioned behaviour: the attenuation losses of the three grating lengths are compensated by the WBG amplification, leading to an effective grating which reflects a signal power equal to that injected, even with a slight gain. On the other hand, Figure 2(b) reveals again that a peak of effective gain is detected, which clearly depends on the grating length: the longer the grating, the grater the gain peak observed (at least in this three grating lengths). A 13.4% gain is obtained with a 10 mm WBG of coupling coefficient $\kappa = 0.27$ mm^{-1}, higher than the 9% obtained with the 5 mm WBG with a more efficient grating ($\kappa = 0.55$ mm^{-1}). As observed in these results, the longer the length, the smaller the coupling coefficient is needed, that is to say, the less effective the Bragg grating must be. These results show up the importance of properly characterizing and selecting the grating and working conditions.

DISCUSSION

A numerical method to simulate the power propagation of light along a Er^{3+}/Yb^{3+} doped waveguide Bragg grating has been implemented successfully. This has allowed to study the interesting combination of efficient reflective Bragg gratings embedded in an amplifying medium. As a result, an effective gain has been numerically observed in the reflected signal power depending on the grating writing parameters and working conditions such as the pumping employed. The results present a very interesting approach to these structures and their potential for amplifying and lasing applications. A deeper study must be developed in order to adequately design and optimize the WBG grating parameters and working conditions, as well as a theoretical-experimental comparison.

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