Improving the stability of distributed-feedback tapered master-oscillator power-amplifiers

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Abstract—**We consider theoretically the lasing properties of distributed-feedback master-oscillator power-amplifiers which are compact semiconductor laser devices capable of emitting a high brilliance beam at an optical power of several Watts. Based on a traveling wave equation model we calculate emitted optical power and spectral maps for increasing current injections of the power amplifier. We show that a proper choice of the Bragg grating allows to optimize the laser operation, so that the laser emits a high intensity continuous wave beam and shows no previously observed mode jumps or dynamic instabilities when injection currents are tuned.**

Introduction: Distributed-feedback (DFB) tapered master-oscillator power-amplifiers (MOPAs) are compact semiconductor laser devices capable of emitting a single frequency, diffraction limited continuous wave (CW) beam at an optical power of several Watts. Such lasers are required for many applications including nonlinear frequency conversion, free-space communications, pumping of fiber lasers and amplifiers and laser projectors/beamers. Recently, a MOPA laser emitting a > 10 W high brilliance CW beam at 977 nm has been demonstrated [1].

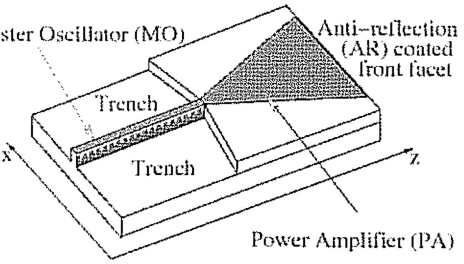

Fig. 1. Scheme of a MOPA device consisting of a DFB Master Oscillator (MO) and a tapered Power Amplifier (PA).

Fig. 1 schematically shows a DFB MOPA. It consists of a distributed feedback (DFB) laser and a flared (or tapered) gain-region amplifier combined on a single chip. MOPAs are characterized by a large amount of structural and geometrical design parameters, and are subject to time-space instabilities like pulsations, self-focusing, filamentation and thermal lensing which yield restrictions to output power, beam quality and wavelength stability. Theoretical models and numerical simulations are needed to optimize the device for certain features required in specific applications.

Model: We perform dynamic simulations of MOPA lasers based on the traveling wave equation model for the complex counter-propagating optical fields $u^{\pm}$ coupled to a parabolic diffusion equation for the carrier inversion N and an ordinary differential equation for the polarization functions $p^{\pm}$ [2]:

$$
\begin{aligned}
&\tfrac{1}{v_g}\partial_t u^{\pm} = \tfrac{-i}{2k_0\bar{n}}\partial_{xx}u^{\pm} + (\mp\partial_z - i\beta - \mathcal{D})\,u^{\pm} - i\kappa u^{\mp};\\
&\partial_t N = D_N\partial_{xx}N + \tfrac{J}{qd} - R(N) - v_{gr}\Re\mathrm{e}\sum_{\nu=\pm} u^{\nu *}[g - 2\mathcal{D}]\,u^{\nu};\\
&\mathcal{D}u^{\pm} = \tfrac{\bar{g}}{2}\,(u^{\pm} - p^{\pm})\,; \quad \partial_t p^{\pm} = \bar{\gamma}\,(u^{\pm} - p^{\pm}) + i\bar{\omega}p^{\pm};\\
&\beta(x,z) = \delta_0 + \delta_n(N) + \delta_T(J) + i\tfrac{g(N,u)-\alpha}{2};\\
&u^{+}(t,0,x) = r_0 u^{-}(t,0,x), \quad u^{-}(t,l,x) = r_l u^{+}(t,l,x).
\end{aligned}
$$

Here, $t \in \mathbb{R}$ denotes time, $z \in [0,l]$ corresponds to longitudinal propagation direction, $x \in \mathbb{R}$ is a lateral space dimension (see Fig. 1), β is a complex dielectric function, which contains the field gain $g(N,u)$, losses α, a built in index variation $\delta_0(x,z)$ and index changes due to carriers $\delta_n(N)$ and injection density $\delta_T(J)$. The coupling coefficient $\kappa = \kappa(x,z)$ models the strength of the distributed feedback in the master oscillator part, it is zero in all other regions. For a detailed description of all model parameters we refer to [2].

Unique existence and smooth dependence of solutions on the data for our model can be proven in a similar way as in [3] by using additional $L^{\infty} - L^{1}$ estimates for the Schrödinger semigroup along x. The model equations are solved numerically using a splitting scheme, where lateral diffraction and diffusion along x are resolved with FFT and the remaining coupled system is integrated using finite differences. The resulting large scale system is solved using multilevel parallel distributed computing (MPI+Multithreading).

Coupling coefficient: In this paper we calculate the emitted optical power and spectral behavior depending on the coupling coefficient κ of the MO. Fig. 2 shows calculated optical output power and spectra for increasing power amplifier current I_{PA} at six values of the coupling coefficient, starting from $\kappa = 250m^{-1}$ up to $\kappa = 5000m^{-1}$. For $\kappa = 250m^{-1}$ we see a slight redshift with periodically occurring mode jumps analyzed in detail in our previous papers [2], [4]. For higher κ the neighboring longitudinal modes are suppressed and the DFB MO becomes less sensitive to the existing residual feedback (due to non-vanishing field reflectivity at the PA facet). Consequently, the transitions or beatings between *neighboring* modes are no more observed. For $\kappa = 1000m^{-1}$, however, jumps between the DFB MO stop-band side modes occur.

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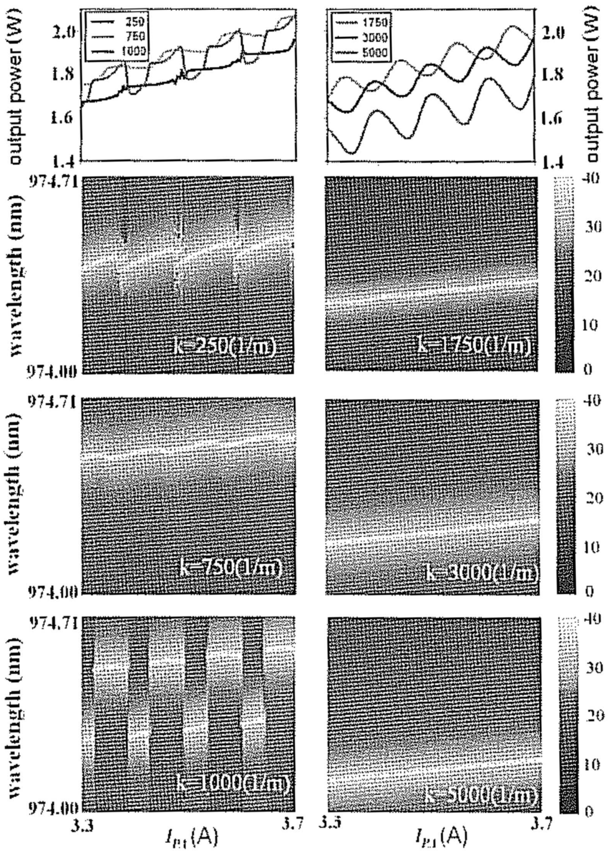

Fig. 2. Top row: simulated optical output power as a function of the PA injection current for different values of coupling coefficient. Rows below: corresponding mapping of optical spectra.

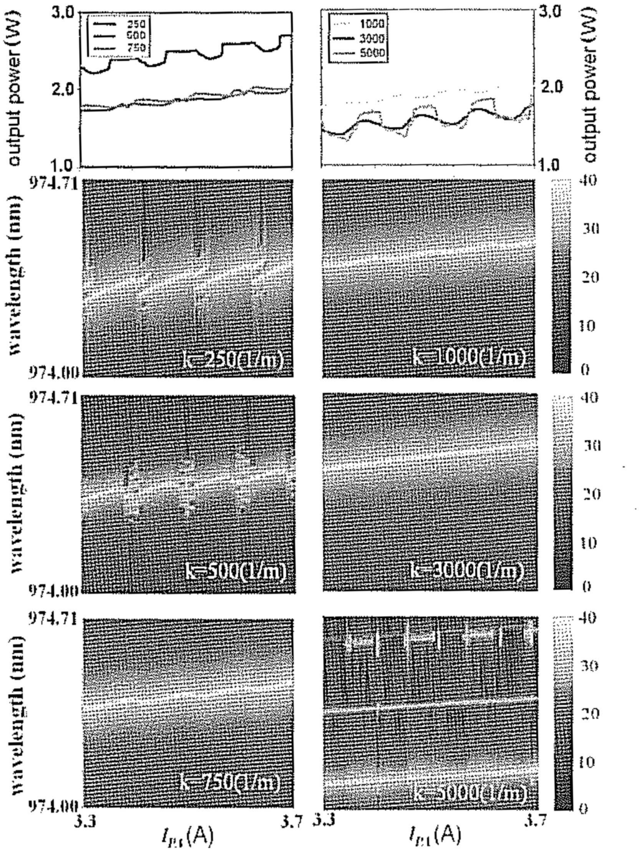

Fig. 3. Similar representation of the computed states as in Fig. 2 for the MOPA lasers with $\lambda/4$-shifted gratings.

For smaller coupling coefficients the lasing wavelength corresponds to the red DFB stop-band side mode. Larger coupling coefficients imply a stronger photon concentration in the middle of the MO, resulting in spatial carrier hole burning. Hence the blue stop-band side modes are selected.

For $\kappa = 750m^{-1}$ and coupling coefficients greater than $1000m^{-1}$ the optical spectrum is stabilized and the dynamic instabilities disappear. Here the MOPA operates at stable CW emission, but the output power is decreasing for larger κ. There exists an optimal range between $1750m^{-1} \leq \kappa \leq 3000m^{-1}$ where the output power is maximal while the device has stable CW operation.

$\lambda/4$ shifted grating: We admit, however, that the mode-jumping behavior shown for $\kappa = 1000m^{-1}$ in Fig. 2 can occur also for other values of κ, depending on the relation between the Bragg wavelength and the material gain peak position. To avoid these stop-band mode transitions we propose to use $\lambda/4$ shifted Bragg gratings, which are supporting a single mode in the middle of the two DFB stop-bands and are weekly sensitive to the optical feedback.

Fig. 3 shows simulation results for such lasers with several values of κ. For $\kappa \leq 500m^{-1}$ and for certain current injections we observe again the beating and the transitions between neighboring modes. On the other hand, for large $\kappa = 5000m^{-1}$ the strong carrier hole burning in the middle of the DFB MO supports the DFB stop-band side modes. The remaining values of κ support a single-mode operation of lasers at CW. Since the simulated output power is decreasing for larger coupling coefficients, an optimal coupling range exists at $750m^{-1} \leq \kappa \leq 1000m^{-1}$.

The qualitative behavior shown in Figs. 2 and 3 does not depend on the phases of the back and front facet reflectivities.

We believe that our work provides a good basis for future study, and, in particular, provides some pointers for improving the output characteristics of MOPA devices.

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