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Analysis of Mode Competition in a Monolithic Master-Oscillator Power-Amplifier emitting at 1.5 µm

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ABSTRACT:

The optical and radio-frequency spectra of a monolithic master-oscillator power-amplifier emitting at 1.5 µm have been analyzed in a wide range of steady-state injection conditions. The analysis of the spectral maps reveals that, under low injection current of the master oscillator, the device operates in two essentially different operation modes depending on the current injected into the amplifier section. The regular operation mode with predominance of the master oscillator alternates with lasing of the compound cavity modes allowed by the residual reflectance of the amplifier front facet. The quasi-periodic occurrence of these two regimes as a function of the amplifier current has been consistently interpreted in terms of a thermally tuned competition between the modes of the master oscillator and the compound cavity modes.

Key words: Master Oscillator Power Amplifier, laser dynamics, high power semiconductor lasers, mode competition

1.- Introduction

A good number of potential diode laser applications require high power and high speed directly modulated sources. The Master Oscillator Power Amplifier (MOPA) architecture is a suitable choice for these applications since large changes in the output power can be obtained at high frequencies with a relatively small current excursion in the Master Oscillator (MO). Monolithically integrated MOPAs are two sections devices, an index guided single lateral mode waveguide section acting as a master oscillator, and a Power Amplifier (PA) section. The master oscillator is either a Distributed Bragg Reflector (DBR) or a Distributed Feedback (DFB) laser, while the power amplifier is, in the case of high power devices, a flared section with antireflection coated output facet. In the ideal performance of these devices the single lateral and longitudinal mode generated by the oscillator is launched into the amplifier section where it undergoes free diffraction and amplification while keeping its initial beam quality.

In the last years, a good deal of progress has been achieved in the development of monolithically integrated MOPA sources. 12 W output power in continuous-wave (CW) regime has been demonstrated at 1064 nm as well as pulse generation with 42 W peak power and 84 ps pulse width [1]. At an eye-safe wavelength close to 1.5 µm, commercial devices achieve 1.6 W output power in CW conditions and recently we have demonstrated the generation of 100 ps wide pulses with peak power up to 2.7 W at 1 GHz by Gain-Switching (GS) the MO section of these devices [2]. However, the obvious advantages of integrated

MOPAs in comparison with their hybrid versions in terms of compactness and integrability can be jeopardized by the appearance of multiple emission instabilities even when both sections are driven in CW conditions [2-8]. Many of these instabilities are related with the appearance of modes of the whole MOPA cavity acting as a compound cavity due to the residual reflectance of the amplifier front facet that allows optical feedback. Interaction and competition between these modes and with the MO mode has been demonstrated to result in ripples in the Power-Current characteristics and self-pulsations caused by the mode beating at the frequency of the spacing between neighboring modes in the optical spectra [2-3, 6-8].

In our previous work [3], we have analyzed the emission characteristics of a monolithic MOPA emitting at 1.5 µm under specific injection conditions in the neighborhood of a ripple of the P-I characteristics. In this work we present a more extend and detailed experimental study of the mode competition and hopping based on the analysis of the maps of the optical and RF spectra as a function of the PA injection current for a constant injection of the MO section. The experimental set-up is briefly described in section 2. In section 3 the experimental results are presented and discussed and the conclusions are drawn in section 4.

2.- Experimental

The device is a commercially available MOPA with emission wavelength close to 1.55 µm (QPC Lasers 4715-0000). It consists of a DFB Master Oscillator and a tapered Power Amplifier. The total device length is around 2.5 mm, and its output facet width is around 250 µm. The device is p-up mounted on a c-mount. More details about devices from this manufacturer can be found in [9].

An experimental set-up was designed for driving separately each section as shown in Fig. 1. A CW current source directly supplies the current I_{PA} to the PA section and a CW current source supplies the current I_{MO} to the MO section. All the measurements were performed at a constant temperature of 20°C.

The output optical power was measured with a broad area thermal detector (Gentec UP19K-30H-H5), placed close to the MOPA output facet and slightly tilted to avoid undesired optical feedback.

The spectral measurements were performed by collecting a fraction of the emitted light through a lensed single-mode fiber (SMF) placed at about 200 µm from the MOPA output facet. We made sure that at the driving conditions studied, the light collected by the fiber had the same spectral distribution that the total emitted power. An Optical Isolator (OI) was used to avoid back reflection from the set-up into the device. Light was split by a fiber optical coupler (10:90) and its output ports were connected to an Optical Spectrum Analyzer (OSA, Ando AQ6315) with a resolution of 0.05 nm) and to a 45 GHz photodiode (PD2, New Focus 1014) and an Electrical Spectrum Analyzer (ESA, Agilent E4446A) with 44 GHz frequency range.

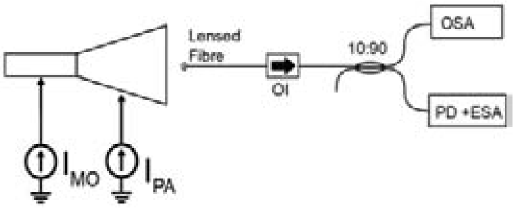

Fig. 1: Schematics of the experimental set-up. I_{MO}: Master oscillator current. I_{PA}: Power amplifier current. OI: Optical isolator. OSA: Optical spectrum analyzer. ESA: Electrical spectrum analyzer. PD: Photodiode.

3.- Experimental results and discussion

Figure 2 shows the power-amplifier current (P-I_{PA}) characteristics of the MOPA for a constant injection level of the master oscillator, I_{MO} = 30 mA. A complete P-I_{PA} characteristic of the device for several constant values of I_{MO} were presented and discussed in [3]. The most relevant feature for the present discussion is the appearance of clear ripples in the P-I_{PA} curve. For the specific injection conditions marked as A (I_{PA} = 4.08 A, I_{MO} = 30 mA) and B (I_{PA} =

3.93 A, I_{MO} = 30 mA) in Fig. 2, significant spectral differences were found in [3].

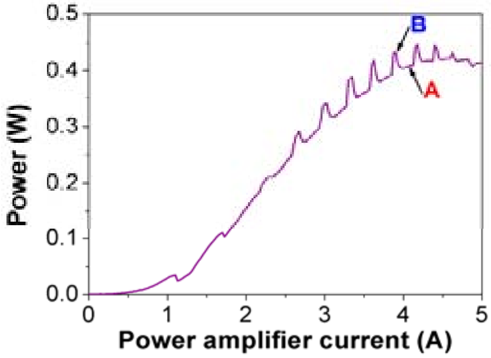

Fig. 2: Output power of the MOPA as a function of the current injected in the PA section for a constant current injected in the MO section, I_{MO} = 30 mA

Since A and B are located between two ripples and in the previous ripple respectively, and since similar ripples appear along the entire curve, it seems rather natural to add the spectral information and to plot a complete spectral map as a function of I_{PA}. This is done in Fig. 3.

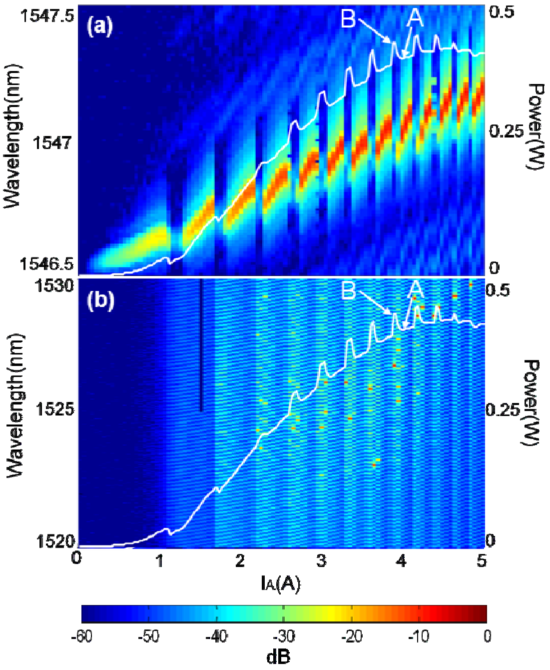

Fig. 3: Color map of the optical spectra of the MOPA as a function of I_{PA} for I_{MO} = 30 mA. The map is shown in two spectral regions, 1546.5 - 1547.5 nm (a) and 1520 – 1530 nm (b). The P-I_{PA} curves have been superimposed for reference. The intensity has been normalized to the maximum intensity in the whole map and plotted in a logarithmic color grading. The black vertical line at about I_{PA} = 1.5 A in (b) is an artifact.

The figure is a color map of the spectral distribution of the optical power in the entire range of I_{PA}, for I_{MO} = 30 mA. The intensity has been normalized to the maximum intensity in the whole map and has been plotted in a logarithmic color grading. The spectral region of the main laser peak is plotted in Fig 3(a) and the spectral region 1520 - 1530 nm is plotted in Fig 3(b), in a different wavelength scale. The P-I_{PA} characteristic (total optical power) has been superimposed on each plot for reference. Vertical fringes with sharp edges are apparent in both maps. The edges of each fringe are coincident in both spectral regions with the rise and the fall of a ripple in the P-I_{PA} curve. In each fringe, an anti-correlation between the optical power in each spectral region is also clearly seen. At this point, the individual spectra corresponding to injection conditions in close fringes may help understanding the entire picture. Figs. 4a and 4b show respectively the spectra in logarithmic scale corresponding to the conditions A and B marked in Fig. 3.

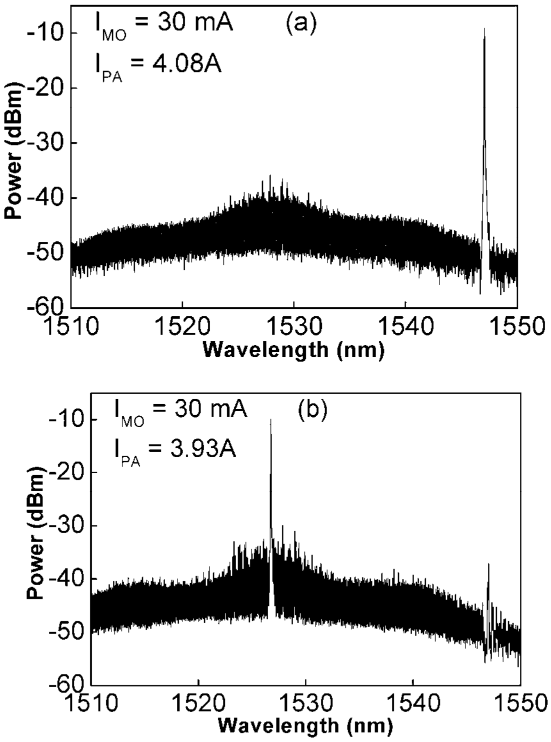

Fig. 4: Logarithmic plot of the optical spectra of the MOPA under injection conditions A (a) and B (b).

Under conditions A, almost all the power of the device is emitted in the DFB mode at about 1470 nm, whereas a minimum Amplified Spontaneous Emission (ASE) appears in the region 1510 - 1545 nm. However, in the previous fringe (conditions B) the situation is quite the opposite. Now, most of the power is emitted in the region 1510 – 1545 nm whereas the power emitted at about 1547 nm has dramatically dropped down. This behavior has been discussed in [3] in terms of mode competition between the Fabry-Perot-like longitudinal modes of the compound cavity and the DFB mode at about 1547 nm. The prevalence of a specific mode depends on slight changes in the injection conditions. Coming back now to the maps of Fig.3, it is clear that the injection conditions allowing a specific operation mode repeat quasi-periodically as a function of the amplifier current and that not only the total power emitted in a ripple but also its spectrum is different from the spectrum of the light emitted under injection conditions in the close vicinity. In line with previous reports on 980 nm MOPAs [6-8], our qualitative interpretation of this behavior is as follows: At injection conditions A-like the MO lase in the DFB mode selected by the design of its grating and the device behaves as expected from a MOPA: the laser beam generated in the MO section undergoes amplification in the PA section without spectral changes. As I_{PA} increases, the heat generated in the amplifier section slightly increases the temperature of the MO section and therefore, the spectral position of the DFB mode shifts to a higher wavelength due to the thermal increase of its refractive index. The mode competition between the compound cavity modes in the region of high material gain and the DFB peak results in the prevalence of this peak. However, a further increase of I_{PA} eventually shifts the DFB peak into a region in which the design of the DFB diffraction grating does not provide the mode with enough gain to compete with the compound cavity modes. This value of I_{PA} marks the edge of the fringe in both spectral regions. For higher values of I_{PA} the spectra results in a B-like fringe. Now the compound cavity works as a laser emitting in a mode in the high material gain region (1520 -1535 nm) (Fig. 3b). The emission at about 1547 nm is virtually absent while the comb of ASE peaks of the compound cavity becomes brighter in the region 1520 - 1535 nm. It is worth to point out that the active mode hopping in these conditions results in a seeming distribution of the optical power among several modes, such that none of them seems to have the power lacking in the 1547 nm region. This is obviously only a consequence of the fast dynamics of mode hopping in comparison with the slow process of recording the spectra. A further increase of I_{PA} eventually leads to the required temperature increase of the MO section for the next DFB mode to reach enough gain for lasing. At this point the device comes back to the A-like operation mode in the next fringe.

Further insight into the mode dynamics can be gained by plotting the map of the RF spectra in a similar manner. Fig. 6 shows this map in logarithmic scale. Again the P-I_{PA} characteristic has been plotted for reference.

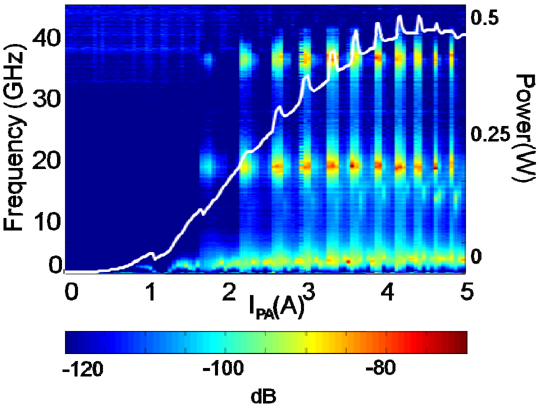

Fig. 5: Color map of the RF spectra of the MOPA as a function of I_{PA} for I_{MO} = 30 mA. The RF power is plotted in relative units in a logarithmic color grading. The P-I_{PA} curve has been superimposed for reference.

The concurrence of the injection conditions at which the ripples and the RF peaks appear is also apparent all along the map. The RF spectra under conditions A and B were analyzed in [3]. What was locally analyzed there is here confirmed in the entire range of I_{PA}. Namely, the active competition between compound cavity modes under B-like injection conditions results in a self-pulsation regime due to the beating of consecutive compound cavity modes.

4.- Conclusion

In conclusion, for a monolithic 1.5 µm DFB-MOPA we have demonstrated in a wide range of injection conditions that the mode competition between the compound cavity modes and the DFB mode results in two essentially different operation modes that alternate quasi-periodically as a function of the current injected in the amplifier section. This result enlightens the complex dynamics of monolithic MOPA devices under CW regime.

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