40 GHz MMIC Driver of Electro-Absorption Modulator for high-speed optical pulse generation

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Abstract — **For the next generation of high-speed optical communications (4x40Gbit/s OTDM), the availability of very short pulse sources is crucial. This work deals with optical pulse sources using electro-absorption modulators (EAM). With the aim of matching a 100µm-long EAM, a 40GHz MMIC driver was designed and fabricated using a GaAs PHEMT 0.15µm process. To handle the actual electro-optical objectives of the Driver+EAM function (short pulse ~5ps, high extinction ratio ~30dB) we have developed a specific design method, which includes modeling techniques of EAM and CAD-oriented electro-optical design rules. Preliminary optical measurements of the first assembled optical modules (with & without driver) show that the driver leads to more than 10dB improvement for the electro-optical response of the EAM pulse source in the 39.7-42GHz band.**

I. Introduction

Many research efforts are now focusing on the next high bit-rate hierarchy of 160Gbit/s per wavelength channel by optical time division multiplexing (OTDM) of 40GHz optical sources. In combination with wavelength division multiplexing (WDM), those technologies allow to increase the overall capacity up to Tbit/s optical communications.

To ensure OTDM systems with low power penalties the availability of very short pulse sources exhibiting low chirp and high extinction ratios is crucial. The competition is still open between the different types of optical pulse sources such as gain-switched lasers, mode-locked lasers and lasers followed by EA modulators.

This paper deals with the EAM-based pulse source [1-2] that has the advantages of low-chirp, low-jitter and high-speed. It works by applying a high-frequency modulation voltage to the EAM with the view to fully exploring its on-off optical absorption characteristic, hence generating very short pulses with high extinction ratios.

In this work, focus is put on the design issues of a 40 GHz electronic driver needed to match the capacitive load of the EAM and to drive it with several volts of output swing. In order to efficiently optimize the optical pulse characteristics of the driver-modulator function, we have developed a specific design method of the electronic driver circuit. A 100µm-long InP-based EAM component has been developed and the circuit design method has been applied to a 40GHz MMIC driver using GaAs PHEMT 0.15µm OMMIC technology. The assembled optical module integrates the driver and the EAM components to realize a 40GHz repetition rate pulse source operating at 1550nm with short pulse width of ~5ps and extinction ratio of 30dB using 0dBm electrical input power.

II. Design method of the EAM-Driver

A. Modeling Techniques of the EAM

The operating principle of EAM is based on the modified absorption spectrum of a semiconductor when excited by an electrical field (Franz-Keldysh and Stark effects). The EAM is a semiconductor waveguide, in which changing the externally applied voltage significantly changes the absorption of the light crossing it. This electro-optical characteristic corresponds to the measured curve at 1550nm of its optical extinction ratio ER versus intrinsic reverse bias V_M (Fig. 1). EAM components are designed and optimized to reach ultra broadband performances and the highest possible extinction ratio combined with the smallest possible drive voltage.

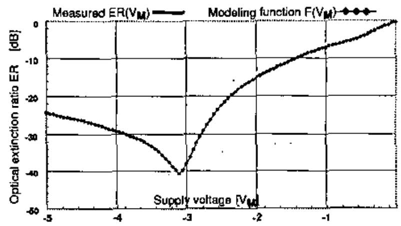

Fig. 1: Measured and modeled optical extinction ratio of the 100µm-long InP-based EAM at 1550 nm

The actual goals of Driver+EAM optimization are not directly linked to conventional amplifier characteristics (gain, power, [S]...) but to the time domain characteristics of the generated optical pulses (width, extinction ratio). The most critical issue when designing the high-frequency driver amplifier is to accurately take into account electrical and electro-optical characteristics of the EAM component during the CAD step. With this aim, we have developed a specific design methodology including dedicated modeling and CAD techniques.

On the one hand, in order to account for the high-frequency electrical characteristics of the EAM, the first design step consists in modeling the modulator by an equivalent electrical circuit (Fig. 2). This model includes the non-linear dependence of Rs and Cs on the intrinsic modulation voltage V_M. It clearly shows that an important design issue of the driver will be to match such a capacitive load, which is far away from 50Ω.

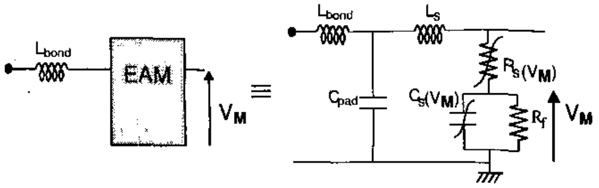

Fig. 2: High-frequency electrical model of the InP-based EAM.

On the other hand, so as to account for the electro-optical EAM characteristics, the next design step consists in modeling its measured extinction ratio ER using a suited rational function $F(V_M)$ (Fig. 1).

$$F(V_M)=\frac{A_0+A_1\times V_M+A_2\times V_M^2+A_3\times V_M^3+A_4\times V_M^4+A_5\times V_M^5+A_6\times V_M^6+A_7\times V_M^7}{1+B_1\times V_M+B_2\times V_M^2+B_3\times V_M^3+B_4\times V_M^4+B_5\times V_M^5+B_6\times V_M^6+B_7\times V_M^7+B_8\times V_M^8} \quad (1)$$

The first two modeling steps enable us to directly implement the electrical and electro-optical characteristics of the EAM within the circuit CAD tool. On the one hand, those models are used during the electronic driver CAD to optimize the input matching and the voltage gain of the Driver+EAM function. On the other hand, they enable to simultaneously compute the time domain characteristics of the output optical pulses (width, extinction ratio) under large signal voltage modulation (Fig. 3), which are the actual goal specifications of the short pulse source.

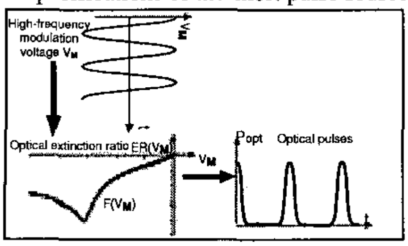

Fig. 3: Principle of optical pulse generation using EAM.

According to Fig. 3, the high-frequency modulation voltage swing $V_M(t)$ should be as large as possible to fully sweep the ER curve of the EAM so as to generate optical pulses with a maximum extinction ratio and a minimum pulse width. In the case of the 100μm-long InP-based EAM developed in this study, an intrinsic peak to peak modulation voltage V_M of about $4V_{p\text{-}p}$ is needed to generate very short optical pulses with extinction ratios higher than 30 dB and pulse widths ranging from 5 to 6 ps.

B. Active Driver Topology

Key transistor technology requirements for the electronic EAM-Driver are high breakdown voltage and transition frequency to reach the required voltage swing of the high-frequency modulation voltage V_M. The choice of an active cascode cell (Fig. 4) theoretically enable to double the breakdown voltage limit of a given transistor technology and to achieve higher gain and isolation at high frequencies. In the 39-43 GHz frequency band, the active cascode cell was optimized in terms of transistor size (6x20μm) and passive network (L, R and Ca). Its optimum output load Z_{opt} and bias points have been determined under large signal excitations by using the substitute generator technique [3].

The GaAs PHEMT 0.15μm OMMIC technology enables ~15V saturated output voltage for an ideal cascode cell. In order to compensate for the insertion losses of the output matching network and the EAM, such an ideal output voltage swing of the cascode cell is needed to reach the specification of more than $4V_{p\text{-}p}$ modulation voltage V_M without saturating the driver. The intrinsic cascode cell network and its output matching network are designed to reach the best tradeoff between optimum voltage matching Vc of the cascode cell, intrinsic stability and optimum transfer to the modulation voltage V_M. Such a trade-off leads to $\sim 9V_{p\text{-}p}$ cascode output voltage Vc_{sat} at saturation input power, and $\sim 5V_{p\text{-}p}$ cascode output voltage Vc to reach $4V_{p\text{-}p}$ modulation voltage V_M at 0dBm input power.

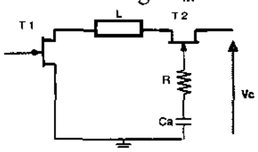

Fig. 4: Cascode cell topology

C. CAD method of the electronic EAM-Driver

The CAD method of the electronic EAM-Driver is different from a conventional S-parameter optimization of classical 50Ω amplifiers. The actual goals of the EAM-Driver are the peak to peak intrinsic modulation voltage V_M of the EAM and the resulting time domain waveforms of the generated optical pulses (width, extinction ratio).

With this aim, we have developed a specific CAD oriented method of the EAM-Driver circuit implementing a dedicated simulation bench (Fig. 5), which is made of two linear 2-port circuits and one non-linear 2-port circuit.

- The first linear 2-port circuit C1 integrates the driver made from the cascode cell and its input-output matching circuits followed by the equivalent EAM model and an

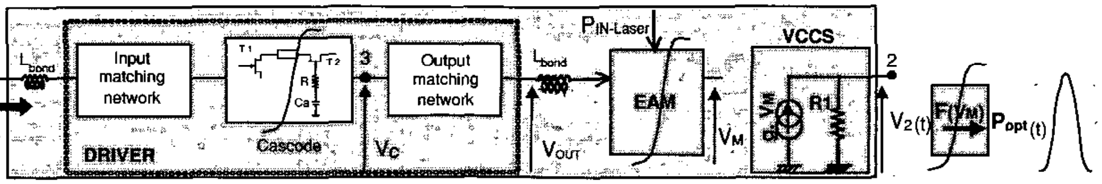

Fig. 5: CAD implementation of the specific driver design method

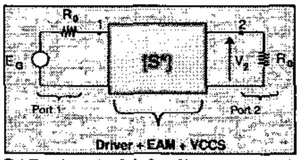

Fig. 6: 2-port CAD circuit C1 for linear optimization

ideal voltage controlled current source VCCS. This circuit is represented on Fig. 5 and defined between ports 1 and 2 (Fig. 6). The modulation voltage V_M controls the output ideal current source for which parameters (g and R_1) are chosen so as to directly link the S_{21}^* parameter to the modulation voltage $V_{Mp\text{-}p}$ and to the available electrical input power P_{INav} (2)(3). Therefore, the specification of $4V_{p\text{-}p}$ modulation voltage V_M at 0dBm input power corresponds to (S_{21}^*>16dB) for this 2-port circuit (4). Moreover, the input matching of the Driver+EAM function can be computed by the S_{11}^* parameter.

$$P_{INav} = \frac{E_G^2}{8.R_0} \qquad S_{21}^* = 2.\frac{V_2}{E_G} \qquad (2)$$

$$g = \frac{1}{R_0} \text{ and } R_1 = R_0 \Rightarrow S_{21}^* = \frac{V_M}{E_G} = \frac{1}{2}\frac{V_{Mpp}}{\sqrt{8.R_0.P_{INav}}} \qquad (3)$$

$$P_{INav} = 0dBm \text{ and } V_{Mpp} \geq 4V \Rightarrow S_{21}^* \geq 16dB \qquad (4)$$

- The second linear 2-port circuit C2 is defined between ports 3 and 2 (Fig. 5) including the output matching network of the driver loaded by the EAM. It is used to compute the synthesized load Z_{33} of the active cascode cell since the load presented at port 2 does not influence the driver load because of the isolation due to the ideal VCCS.

- The non-linear 2-port circuit C3 is identical to C1 except that the linear models of transistors and EAM are replaced by their non-linear models. Moreover, this circuit integrates the non-linear transfer function $F(V_M)$ (Fig. 5) modeling the measured optical response of the EAM, and enables to directly compute the time domain waveforms of the generated optical pulses from the computed $V_M(t)$ voltage.

The final simulation bench integrates the three 2-port circuits (C1, C2 and C3) in which duplicate sub-circuits (e.g. output matching network in C1, C2 and C3) are linked by the same component values. As the cascode cell topology was synthesized to reach the required output voltage without saturation, linear simulations can be used to initialize and optimize the input-output matching networks of the driver on the 39-43 GHz frequency band.

Using C1, the driver matching networks are optimized to reach a good input matching (S_{11}^*<-10dB) and the required voltage transfer to V_M (S_{21}^*>16dB) (Fig. 7) when the driver is loaded by the EAM (≠50Ω). At the same time using C2, the output matching network is also optimized and constrained to load the cascode cell by its optimum large signal impedance Z_{33}~Z_{opt}. During that design process of the driver, each topology modification or linear optimization result of (C1, C2) is checked by performing non-linear HB simulations of the C3 circuit. Indeed, thanks to the $F(V_M)$ function, the non-linear circuit C3 enables to directly compute the time domain waveforms of the generated optical pulses as a function of RF input power and frequency in order to check the actual goals of the EAM-driver, which are the pulse width and extinction ratio (Fig. 10). At a given input power, the C3 circuit is also used to determine the optimum reverse bias point V_{M0} of the EAM to obtain the best optical pulse characteristics.

Finally, when saturated, the simulated driver delivers $7V_{p\text{-}p}$ modulation voltage V_{Msat} from $9V_{p\text{-}p}$ cascode voltage V_{Csat}, while at 0dBm input power it delivers $4V_{p\text{-}p}$ modulation voltage V_M from $5V_{p\text{-}p}$ cascode voltage V_C combined with 5ps pulse width and 30dB extinction ratio around 41GHz.

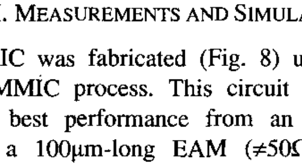

Fig. 7: Non-linear simulation of the peak to peak modulation voltage V_M from 38.5 to 43.5 GHz @ 0 dBm input power

III. MEASUREMENTS AND SIMULATIONS

The MMIC was fabricated (Fig. 8) using a PHEMT 0.15µm OMMIC process. This circuit is optimized to ensure the best performance from an optical module integrating a 100µm-long EAM (≠50Ω). The MMIC includes a specific on-chip bias pad to reverse bias the connected EAM and consumes less than 350mW.

The on-wafer S-parameter measurements of the MMIC are shown in Fig. 9 and compared to the simulated ones in the same environment (L_{bond}=0, 50Ω load). It must be noted that those S-parameters are not the S^*-parameters of the Driver-EAM function and only enable to compare the differences between simulations and measurements since the driver performance is very dependent both on the EAM load (≠50Ω) and on the wire bonding (L_{bond}~0.3nH). Measurements are close to simulations with the same center frequency of 41GHz, a better gain and a reduced bandwidth due to the fact that the cascode cell was biased during on-wafer measurements with a lower bias current to solve class-A instability on 50Ω. Reverse-simulations of Rollet-factor and NDF [4] do not indicate instability that primarily could be explained by the lack of high frequency decoupling capacitors placed close to the chip.

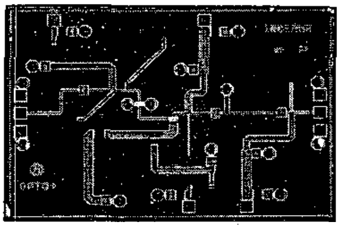

Fig. 8: Photograph of the MMIC driver (2.6x1.8mm^2).

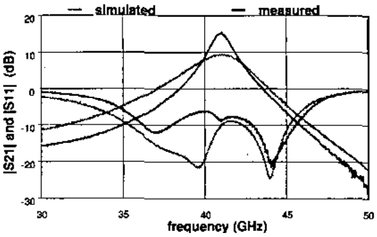

Fig. 9: Measured and simulated S-parameters of the MMIC.

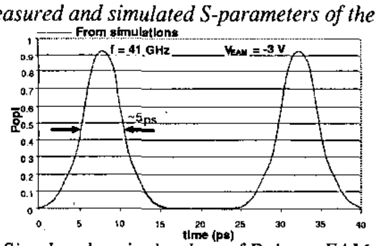

Fig. 10: Simulated optical pulses of Driver+EAM at 0dBm.

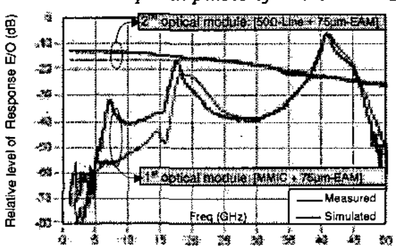

Fig. 11: Measured/Simulated electro-optical response at 1.55μm.

The MMIC driver measurements combined with the EAM model and its extinction ratio $F(V_M)$ enable to simulate the output pulses of the optical module (Fig. 10). At 41GHz, 0dBm driver input power, and -3V EAM bias the simulated optical pulses exhibit a typical 5ps full-width-half-maximum (FWHM) with 30dB extinction ratio.

Two optical modules have already been assembled. The first module integrates the MMIC driver coupled to a 75μm-long EAM while the second module substitutes the MMIC for a 50Ω transmission line. Each module was measured in the same operating conditions with the EAM reverse biased at –3V and excited by 9dBm input optical power delivered by a 1550nm laser. As preliminary tests (Fig 11), the relative electro-optical responses of both module (i.e. $P_{OUT-opt}/P_{IN-elect}$) were measured and compared up to 50GHz showing (13±2.5)dB improvement for the 1st module from 39.7 to 42 GHz (due to the MMIC driver). Given the fact that the driver was not optimized for 75μm-long EAM components, such a preliminary measurement result is very encouraging and the time-domain optical response of the optical module will be soon tested.

At present, new optical modules are under assembly with the MMIC connected to 100μm-long EAM.

IV. Conclusion

The next generation of optical communications (4x40Gbit/s OTDM) requires the availability of very short pulse sources and this work is dedicated to the design of EAM-based optical pulse sources. With the aim of driving a 100μm-long EAM, a MMIC was designed at 40GHz and fabricated using GaAs PHEMT 0.15μm technology. To cope with actual electro-optical goals of the Driver+EAM function (very short pulse, high extinction ratio) we have developed a specific design process, which includes modeling techniques of EAM and CAD-oriented electro-optical design methods. The MMIC measurements are close to the simulated ones and the first assembled optical modules have confirmed the encouraging performance of 40GHz pulse generation using integrated Driver+EAM components for 4x40Gb/s OTDM systems.

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