MODELING PHOTONICS-BASED MICROWAVE FREQUENCY CONVERTER

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ABSTRACT

Developing previously proposed by us a simplified version of microwave-photonics frequency converter based on period-doubling effect in nonlinear optoelectronic element such as cost- and power-efficient long wavelength wafer-fused vertical cavity surface emitting laser we have detailed and updated the simulation results mainly from a device designer’s point of view by numerical modeling using a well-known versatile off-the-shelf soft tool such as MathCAD.

Keywords: microwave photonics, optoelectronic microwave frequency converter, computer aided design

1. INTRODUCTION

Microwave photonics (MWP) is a relatively new branch of photonics science and technology gradually penetrating into telecom (ultra-high-speed optical fiber systems, fiber-to-wireless (FiWi) access networks) and defense (phased-array antenna radars, electronic warfare systems) industries (Urick, McKinney, and Williams 2015). Thanks to capability of MWP devices to accomplish super wideband signal transference and distribution via low loss, lightweight fibers that also have weak dispersion distortion and ultimate electromagnetic immunity, up to this date a plenty of various photonics processing units for transmission, switching, distribution, filtration, and frequency conversion of microwave signals in optical domain has been viewed (Ng 2015). An exciting confirmation is multi-band software-defined coherent radar based on a photonic transceiver that was first in the world constructed by the researchers from CNIT–National Laboratory of Photonic Networks, Italy (Scotti et al. 2015) to demonstrate the practical importance of MWP technology for extending the sensing and signal processing performances of microwave systems.

Previously, we proposed and investigated a simplified version of MWP microwave frequency converter based on period-doubling effect in a semiconductor laser (Belkin, Iakovlev 2015). As a nonlinear element a cost- and power-efficient long wavelength wafer-fused vertical cavity surface emitting laser (VCSEL) was used. This paper details and updates the simulation results mainly from a device designer’s point of view by numerical modeling using a well-known off-the-shelf versatile soft tool such as MathCAD.

2. BUILDING PRINCIPLES

The earlier proposed version of cost-effective MWP microwave frequency converter was based on well-known effect of period doubling (Hemery, Chusseau, and Lourtioz 1990) under modulation of a semiconductor laser by a strong radio frequency sinusoidal signal. For period doubling observation, it is necessary to modulate the laser in super large-signal mode with an injection current cutoff similar to a class C regime in electronic amplifiers. To achieve this, the bias current has to be selected in a near-threshold (but higher) or in the initial part of the quasi-linear area of the laser light-current characteristic. This regime results in generation inside the laser cavity of an optical emission spectrum including a fundamental frequency, its higher harmonic tones, their sub-harmonics, and the products of their mixing with higher tones in addition.

Figure 1 depicts the block diagram of the device under modeling entitled optoelectronic frequency multiplicator (OE-FMP). As one can see, the key part of this OE-FMP is an optoelectronic pair including laser (VCSEL) and working in linear mode photodiode (PD) of p-i-n structure. The electronic band-pass filter in the end of the chain post-processes the converted microwave signal. So, VCSEL is the single nonlinear element of the OE-FMP model.

Figure 1: Block diagram of OE-FMX

3. SIMULATION AND RESULTS

With the goal to define the optimal working area of our VCSEL in the period doubling regime, we performed a preliminary analysis based on quantum well semiconductor laser’s rate equations describing photon and carrier densities nonlinear interaction (Piprek and Bowers 2002):

$$\begin{cases} \dfrac{dN_b}{dt} = \dfrac{\eta_a I(t)}{eV_0} - \dfrac{N_b}{\tau_t} + \dfrac{V_a}{V_b}\dfrac{N}{\tau_e} \\ \dfrac{dN}{dt} = \dfrac{V_b}{V_a}\dfrac{N_b}{\tau_t} - \dfrac{N}{\tau_t} - \left(AN + BN^2 + CN^3\right) - \upsilon_g g(N,S)S \\ \dfrac{dS}{dt} = \Gamma\upsilon_g g(N,S)S - \upsilon_g(\alpha_i + \alpha_m)S + \beta_{sp}\Gamma BN^2 \end{cases} \quad (1),$$

where S is average photon density, N_b *is* average carrier density, η_a is current injection efficiency, e is electron charge, $I(t)=I_b+I_m \cdot cos(\omega_m \cdot t)$ is laser current modulated at angular frequency ω_m with a modulation index $m= I_m/I_b$, α_i and α_m are internal and mirror losses. Gain function is given as:

$$g(N,S) = \frac{g_0}{1+\varepsilon S} \ln\left[\frac{N+N_s}{N_{tr}+N_s}\right] \quad (2)$$

The rest of symbols and their values typical for investigated VCSELs are given in Table I.

Table I: VCSEL model parameters

Parameter	Symbol	Value	Dimension
Gain constant	a	$4.8 \cdot 10^{-20}$	m^2
Linear recombination	A	$1 \cdot 10^8$	m^{-1}
Bimolecular recombination	B	10^{-16}	m^3/s
Auger recombination	C	$3.6 \cdot 10^{-41}$	m^6/s
Active region thickness	D	0.031	um
Material gain	g	$300 \cdot 10^3$	1/m
Threshold current	I_{th}	2	mA
Resonator length	L	1	um
Initial carrier density*	N_0	$1.2 \cdot 10^{24}$	m^{-3}
Negative carrier density	N_s	$-0.8 \cdot 10^{24}$	m^{-3}
Threshold currier density	N_{th}	$5 \cdot 10^{24}$	m^{-3}
Transparency carrier density	N_{tr}	$3.22 \cdot 10^{24}$	m^{-3}
Average mirror reflectivity	R	0.995	
Active region volume	V_a	0.891	um^3
Current blocking volume	V_b	2.779	um^3
Group velocity	v_g	$7.7 \cdot 10^7$	m/s
Active region diameter	w	6	um
Internal cavity loss	α_i	1000	1/m
Spontaneous emission factor	β_{sp}	$7 \cdot 10^{-3}$	
Confinement factor	Γ	0.03	
Nonlinear gain coefficient	ε	$1 \cdot 10^{-24}$	m^3
Internal quantum efficiency	η_i	0.8	
Emission wavelength	λ	1.31	um
Carrier lifetime at threshold	τ_e	2	ns
Electron relaxation time	τ_{in}	0.1	ps
Photon lifetime	τ_p	6.4	ps
* in formula: $g(N)=a(N-N_0)$			

Solving numerically the analytical model (1) in MathCAD soft tool using the embedded BDF-method we obtained for $m>1$ the values of carrier and photon densities versus time, then applying FFT techniques calculated the optical emission spectra. One example of such optical spectrum (upper sideband only) under strong RF modulation is presented in Figure 2. As seen, we succeeded in identification of such dynamic regime of VCSEL under modeling where the signal levels of a fundamental modulation frequency f_m, a sub-harmonic tone $0.5f_m$, and a component at $1.5f_m$ would be near equal and enough to secure the signal-to-noise ratio needed for typical wireless communication systems.

Also, Figure 3 shows the so-called phase-plane portrait of the VCSEL modulated in super large-signal mode. The loop form on the phase trajectory is an attribute for period doubling regime origination. The results presented on Figures 2 and 3 were obtained for bias current $I_b=1,8I_{th}$, and modulation index $m=2$.

In according with the experimental data (Belkin, Iakovlev 2015), a good fit of the simulated and measured OE-FMP output spectra was obtained at input RF signal power of 0 dBm, frequency $f_m=3$ GHz, and DC bias current 3.2 mA, which validated the proposed OE-FMP model. Using them we have also succeeded (see Figure 4) to identify clearly the area of VCSEL bias and modulation indexes at which the signal levels of the fundamental modulation frequency f_m, the sub-harmonic tone $0.5f_m$, and the component at $1.5f_m$ would be comparable to each other in the range inside 10 dB.

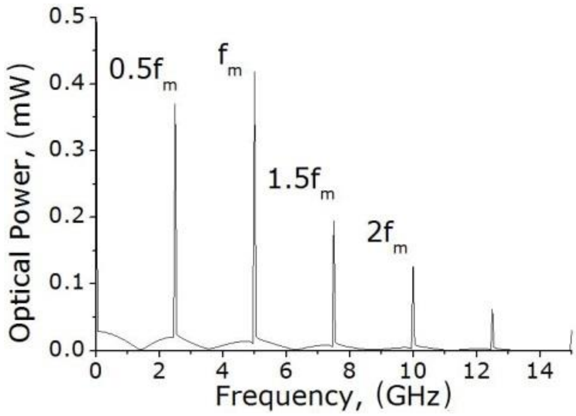

Figure 2: Large signal modulation spectrum.

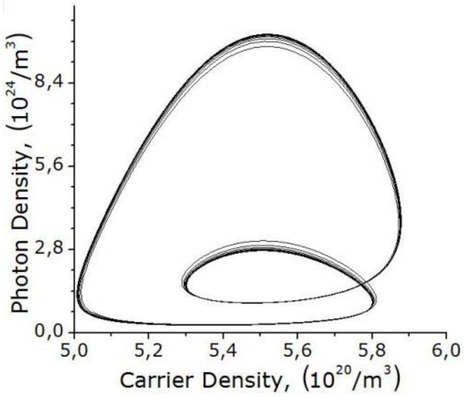

Figure 3: Phase-plane portrait of the VCSEL under simulation modulated in super large-signal mode

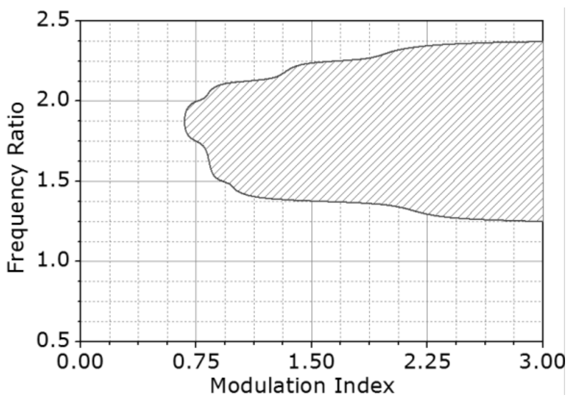

Figure 4: Diagram for VCSEL in sub-harmonic multiplication regime.

Comparing these refined modeling data with the experimental values (Belkin, Iakovlev 2015), we received 1.5-fold reduction for the error of the simulated and measured OE-FMP characteristics.

4. CONCLUSION

Summarizing the modeling results, the main advantage of using VCSELs in optoelectronic sub-harmonic frequency multiplicator are:

(i) large bandwidth (limited solely by the bandwidths of the laser and photodiode);

(ii) application versatility (up-converter and down-converter have the same block diagram);

(iii) conversion loss independence of the position of microwave frequencies within the operation band (absence of the inherent effect of increasing conversion loss with frequency for standard microwave mixers);

(iv) design simplicity;

(v) lower power consumption of the VCSELs (5-10-fold lower than that of edge-emitting lasers);

ACKNOWLEDGMENTS

This work was supported by the Ministry of Education and Science of the Russian Federation under Project RFMEFI60715X0138.

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