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BMAS

VHDL-AMS Modeling of VCSEL including Noise

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Introduction

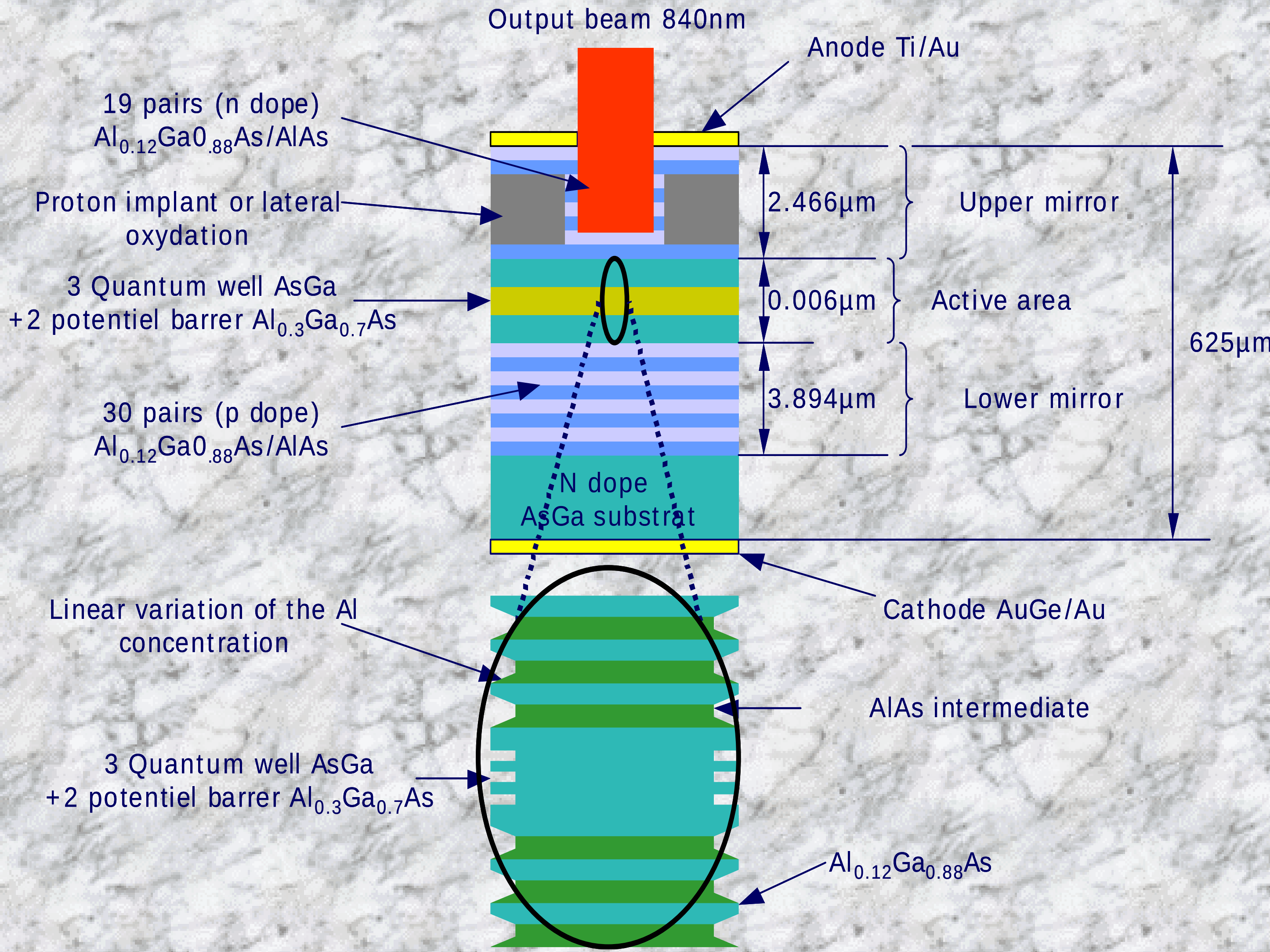
In the last decade, the Vertical Cavity Surface Emitting Laser (VCSEL) appeared as a reliable low-cost high-speed solution for data communication applications and interconnects. It started to challenge the well-established edge-emitting lasers in telecom and data storage applications.

While reliability,performance and cost drove the early adoption of VCSELs, the ease of optical packaging and high modulation bandwidths will continue to ensure success in the marketplace.

The fundamental difference between an edge-emitting laser and VCSEL is the fact that the laser oscillation as well as the out-coupling of the laser beam occur in a direction perpendicular to the gain region and the surface of the laser chip.

VCSEL Model development

The advantages of VCSEL is that the surface emission and the small size make it possible to fabricate very dense two-dimensional arrays of VCSELs, suitable for multi-channels parallel transmission modules.
VCSEL modeling is based on the resolution of semiconductor laser rate equations, expressed for single mode VCSEL operation as function of photon, carrier numbers and phase modulation: S and N , respectively.



VCSEL structure: the schematic of an GaAs processed at Thales Research and Technology (France)

Rates Equation for Electron Number

$$\frac{dN}{dt} = \eta_i \frac{I}{q} - \frac{N}{\tau_n} - G_N (N - N_0) \frac{S}{1 + \varepsilon S}$$

η_i current injection efficiency

I injected current

N Carrier numbers

τ_n Carrier lifetime

G_N Differential gain

N_0 Transparence number

S Photon numbers

ε normalized gain compression factor

Rates Equation for Photon Density

$$\frac{dS}{dt} = -\frac{S}{\tau_p} + \beta \frac{N}{\tau_n} + G_N(N - N_0)\frac{S}{1+\varepsilon S}$$

S Photon numbers

τ_p Photon lifetime

β Spontaneous emission fraction

Noise In Rates Equation

The Langevin Forces are added to last rates equation, they have a correlation function of the form:

$$\left\langle F_i(t) \quad F_j(t')\right\rangle = 2D_{ij}\,\delta(t-t')$$

i,j=S,N and Dij: diffusion coefficient.

$$D_{nn} = R_{sp} * S + \frac{N}{\tau_n} \qquad D_{ss} = R_{sp} * S$$

$$D_{ij} = 0 \quad If\ i \neq j$$

$R_{sp} = \frac{n_{sp}}{\tau_p}$ rate of spontaneous emission

$n_{sp} = \frac{N}{N - N_0}$ spontaneous-emission factor

We assume that, there noise sources behavioral is a Gaussian random process with zero as average value.

VHDL-AMS and Noise

To generate the Langevin forces we use random signal generators. Only white noise sources have been considered.

To generate a white noise source, we use the function *UNIFORM* provided by the library *math_real* of Mentor Graphics ADVanceMS©. This function returns a pseudo-random number x with uniform distribution.

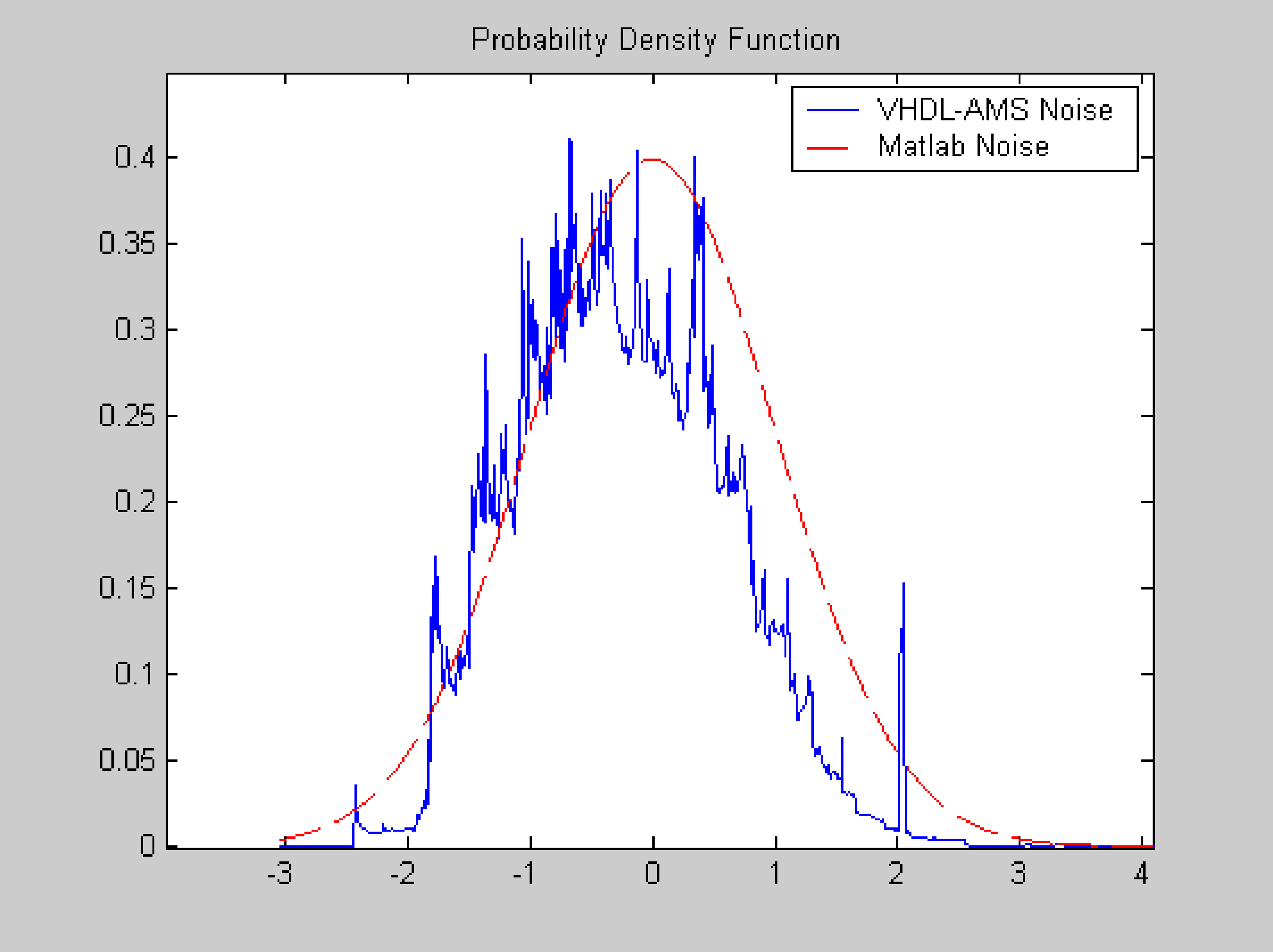
To obtain a white noise with Gaussian distribution, we use Box-Muller transformation, it looks like:

$$y_1 = \sqrt{-2\,ln(x_1)}\,cos(2\pi x_2)$$

$$y_2 = \sqrt{-2\,ln(x_1)}\,sin(2\pi x_2)$$

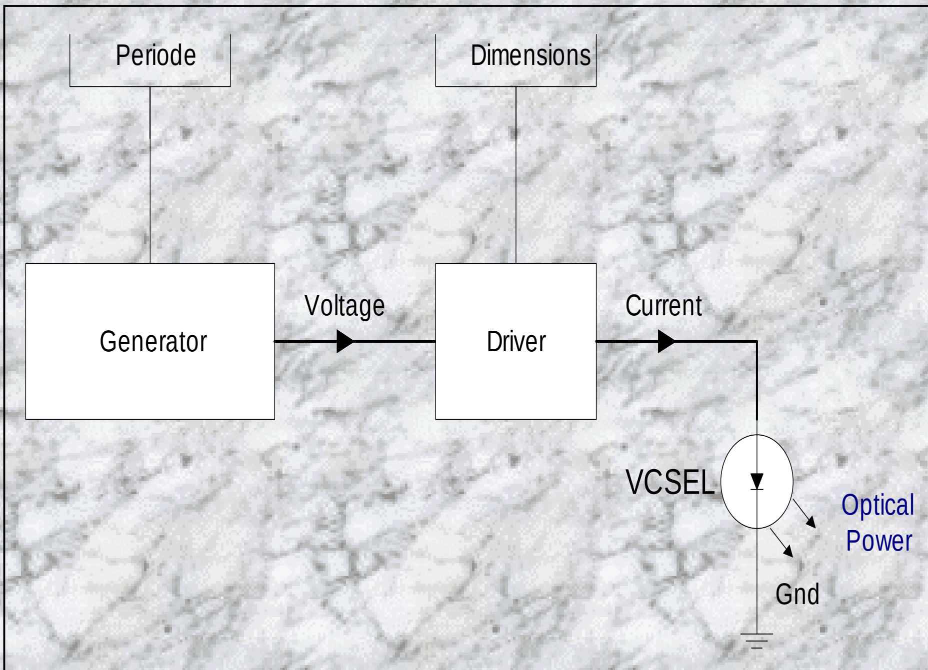
```
Detection:process
        variable seed1:integer:= 3456 ;
        variable seed2:integer:= 4563 ;
        variable    unf   : real;
     begin
                    wait for    tau  ;
     uniform(seed1,seed2,           unf  );
                    If  unf  >0.0 Then  out1<=          unf  ;
                                                 ELSE  null;
                    End If;
     uniform(seed1,seed2,           unf  );
                    If  unf  >0.0 Then        out2<=     unf  ;
                                                  ELSE    null;
                    End If;
 end process;
```

A random signal generator process written with VHDL-AMS and using the *UNIFORM* statement.



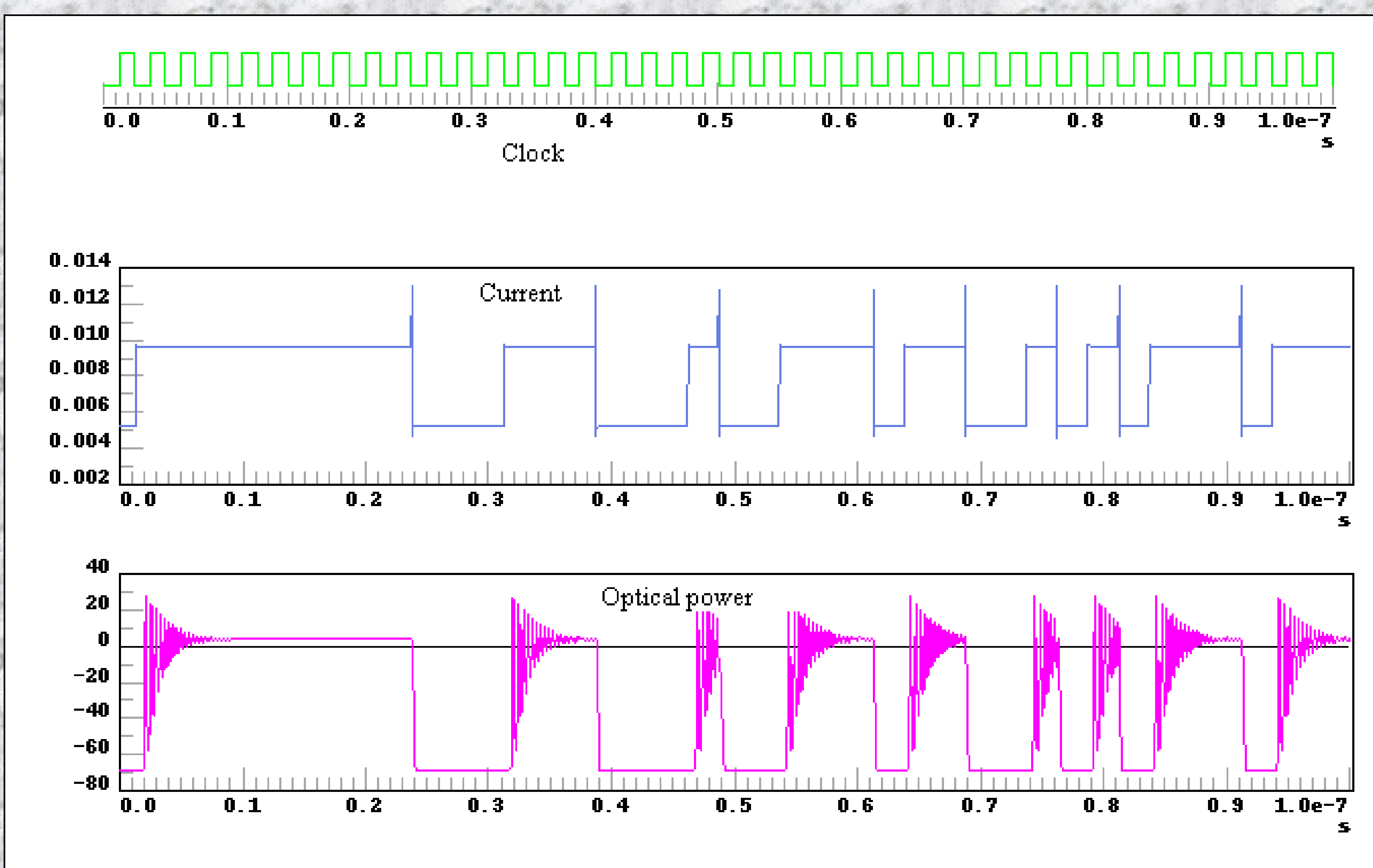
Comparison between the Probability Density Function obtained by an ideal Matlab© simulation and the implemented VHDL-AMS model.

```
ARCHITECTURE be_laser OF laser IS


--Laser rate equations

N'dot == etai * I/physical_Q - N/TauN - Go * (N - No) * S / (1.0 + eps * S ) + Fn ;

S'dot == - S/TauP + Beta * N / TauN + Go * (N - No) * S / (1.0 + eps * S ) + Fs;

Psi'dot ==AlphaH / 2.0 * ( Go * (N - No)/(1.0 + eps * S) - 1.0/TauP ) + Fpsi;

--Threshold current

Ith == a0 + a1 * Ti + a2 * Ti**2.0 + a3 * Ti**3.0 + a4 * Ti**4.0 ;

--Noise Source

Fn   == Vnoise  * sqrt( Dnn ) ;

Fs   == Vnoise2 * sqrt( Dss ) ;

Fpsi == Vnoise3 * sqrt( Dpsipsi )  ;

--Diffusion coefficient

Dnn     ==  Rsp * S+N / TauN;

Dss     == Rsp * S ;

Dpsipsi == Rsp / ( 4.0 * S ) ;

--Spontaneous emission

Rsp == nsp / TauP ;

nsp == N / ( N - No) ;

--Optical power

Popt == (physical_H * nu * Alpham * Vg / 2.0 ) * S ;


END ARCHITECTURE be_laser;
```



Optical transmitter with random generator

```
clock <= not clock after ( periode);
 PROCESS
  BEGIN
    wait until clock ='1';
  FOR i IN 1 TO n-1 LOOP
     SR(i+1) <= SR(i);
     IF SR(i) ='1'  THEN  Vout_int <=V_high;
                           ELSE Vout_int <= V_low;
      END IF;
    END LOOP;
    CASE n IS
       when 7 =>   SR(1) <= SR(3) xor SR(7);
       when 10 => SR(1) <= SR(3) xor SR(10);
       when 15 => SR(1) <= SR(1) xor SR(15);
END CASE;
 END PROCESS;
Vout == Vout_int'ramp;
END;
```



Transient Simulation results: clock, injection current and optical power