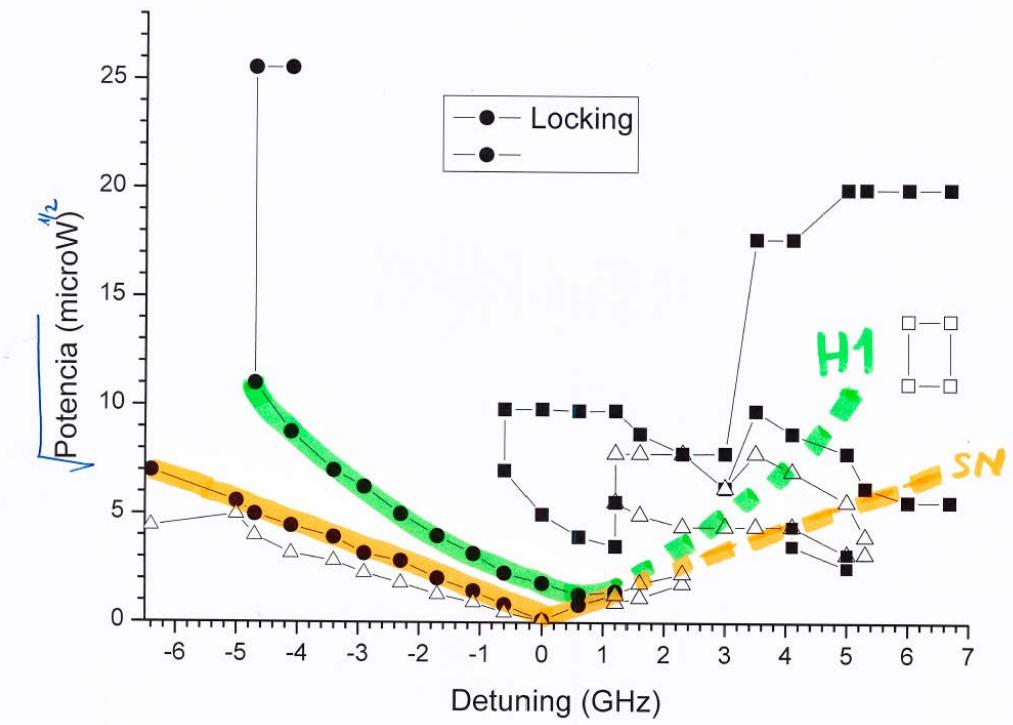
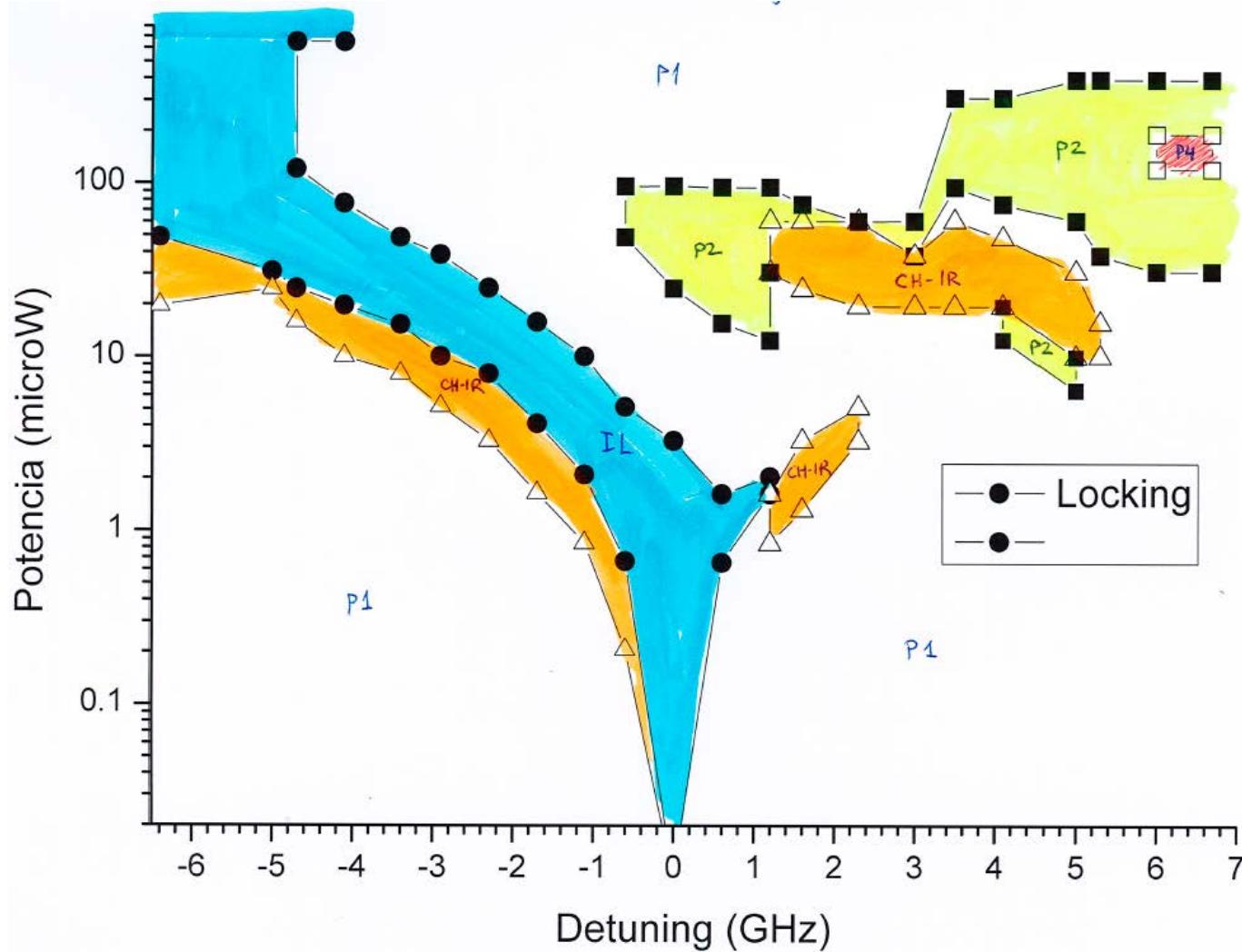


# Optical injection in gain-switched OFCs

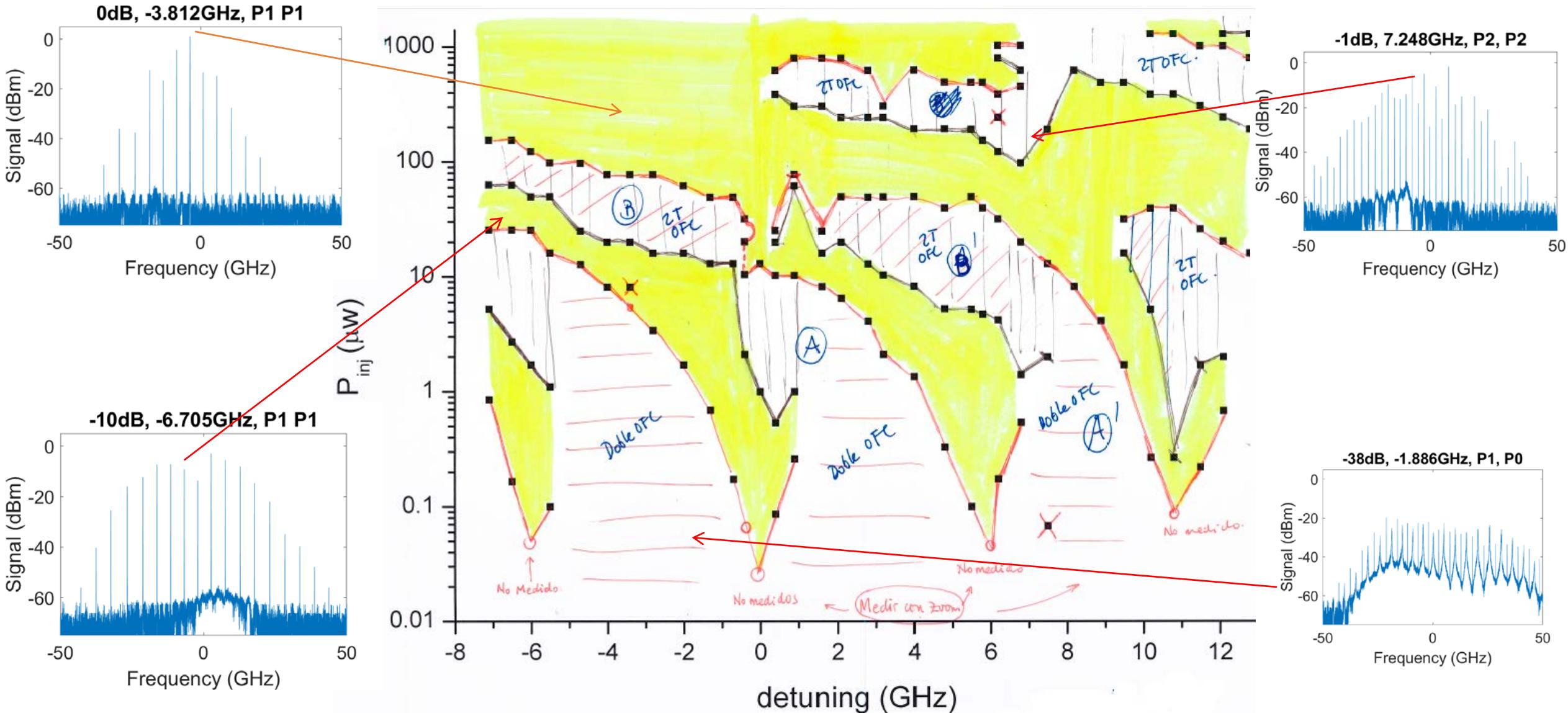
UPM+IFCA

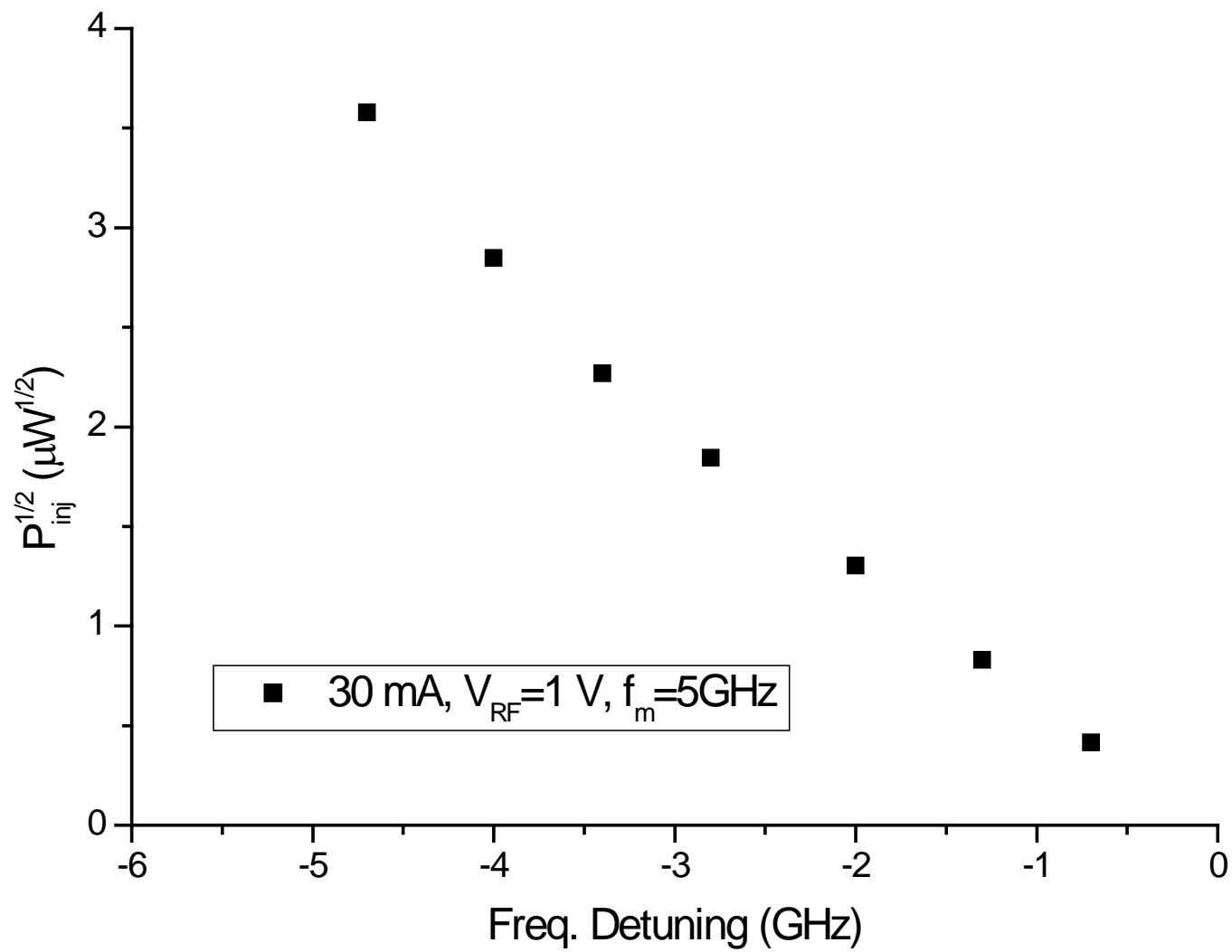
# Experiments with DML

# CW-DML subject to optical injection ( $I=30$ mA, $I_{th}=14$ mA)



## Sinusoidally GS-DML subject to optical injection ( $I=30\text{ mA}$ , $V_{rf}=1\text{ V}$ , $f_{mod}=5\text{ GHz}$ )





Medidas hechas para  $I=21$  mA,  $f_{mod}=5$  GHz,  $V_{rf}=0.4$  V  
 $f_{mod}=10$  GHz,  $V_{rf}=0.3, 0.6, 1.2, 1.8$  V

$I=32$  mA,  $f_{mod}=5$  GHz,  $V_{rf}=1$  V  
 $f_{mod}=10$  GHz,  $V_{rf}=1.2$  V

Análisis por hacer

# Theory with single-polarization mode VCSEL subject to optical injection

Single-mode CW laser locked to OI: frecuencia: la de la inyección  
fase: fija y dada por la inyección

Single-mode GS-OFC locked to OI: frecuencias: inyección  $\pm n f_{\text{mod}}$

¿Fase?

# The model: single polarization mode VCSEL

$$\begin{aligned}\frac{dE_x}{dt} = & -(\kappa + \gamma_a)E_x - i(\kappa\alpha + \gamma_p)E_x \\ & + \kappa(1 + i\alpha)(DE_x + inE_y) + \kappa E_{inj,x} e^{i(2\pi\nu_{inj}t + \delta)} \\ & + \left( \sqrt{\frac{R_+}{2}}\xi_+(t) + \sqrt{\frac{R_-}{2}}\xi_-(t) \right)\end{aligned}$$

Solitary CW laser emitting in y-direction

$$\begin{aligned}\frac{dE_y}{dt} = & -(\kappa - \gamma_a)E_y - i(\kappa\alpha - \gamma_p)E_y \\ & + \kappa(1 + i\alpha)(DE_y - inE_x) + \kappa E_{inj,y} e^{i2\pi\nu_{inj}t} \\ & + i \left( \sqrt{\frac{R_-}{2}}\xi_-(t) - \sqrt{\frac{R_+}{2}}\xi_+(t) \right)\end{aligned}$$

Linearly polarized injection in y-direction

$$\begin{aligned}\frac{dD}{dt} = & \frac{I}{e\Delta N_t} - R(D) - \gamma[D(|E_x|^2 + |E_y|^2) \\ & + in(E_y E_x^* - E_x E_y^*)]\end{aligned}$$

$$E_{inj,x} = E_i \sin \theta_p, \quad E_{inj,y} = E_i \cos \theta_p$$

$$\begin{aligned}\frac{dn}{dt} = & -\gamma_s n - \gamma[n(|E_x|^2 + |E_y|^2) \\ & + iD(E_y E_x^* - E_x E_y^*)]\end{aligned}$$

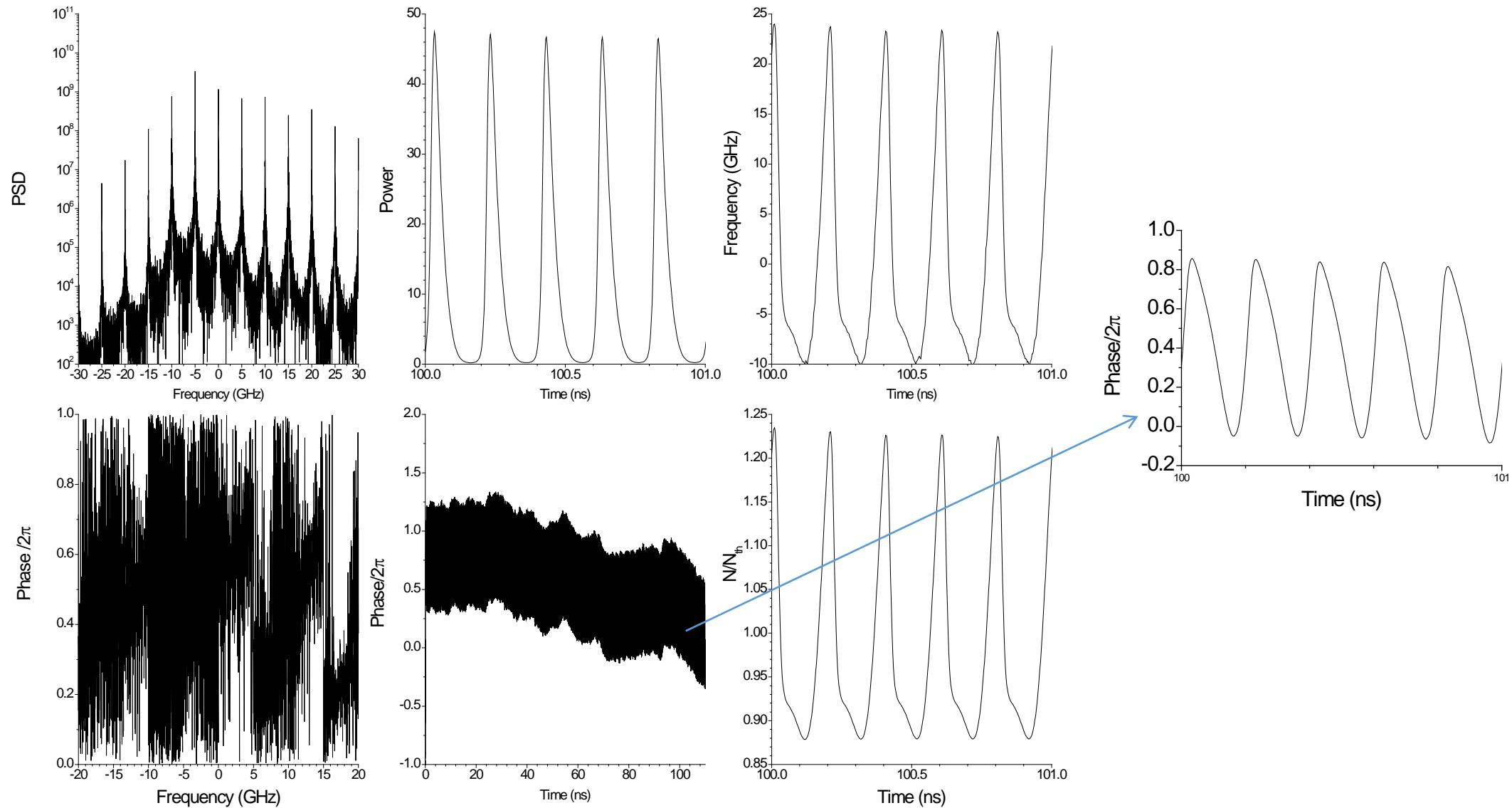
$$R_\pm = \beta_{SF} \gamma \left[ (D \pm n) + \frac{G_N N_t}{2\kappa} \right]$$

$$R(D) = A(D + D_t) + B(D + D_t)^2 + C(D + D_t)^3$$

$$I(t) = I_0(1 + m \cos(2\pi f_m t))$$

$$D_t = N_t / \Delta N_t, \text{ and } \Delta N_t = N_{th} - N_t$$

Optical Injection: NO. Freqs referred to solitary y-CW  
Current Modulation: YES.  $m=1$ ,  $I_{bias}=11.5$  mA,  $f_{mod}=5$ GHz



## Locked optical spectrum with two lines

$$E(t) = A_0 \exp(i\phi_0) + A_1 \exp(i(2\pi f_m t + \phi_1)) = A(t) \exp(i\phi(t))$$

$$A^2(t) = E(t)E^*(t) = A_0^2 + A_1^2 + 2 A_0 A_1 \cos(2\pi f_m t + \phi_1 - \phi_0)$$

$$\tan \phi(t) = (A_0 \sin(\phi_0) + A_1 \sin(2\pi f_m t + \phi_1)) / (A_0 \cos(\phi_0) + A_1 \cos(2\pi f_m t + \phi_1)).$$

If  $A_1 \ll A_0$ ,  $|\sin \phi_0| \ll 1$  entonces  $\phi(t) \sim \phi_0 + A_1 \sin(2\pi f_m t + \phi_1) / A_0$

## Locked optical spectrum with three lines

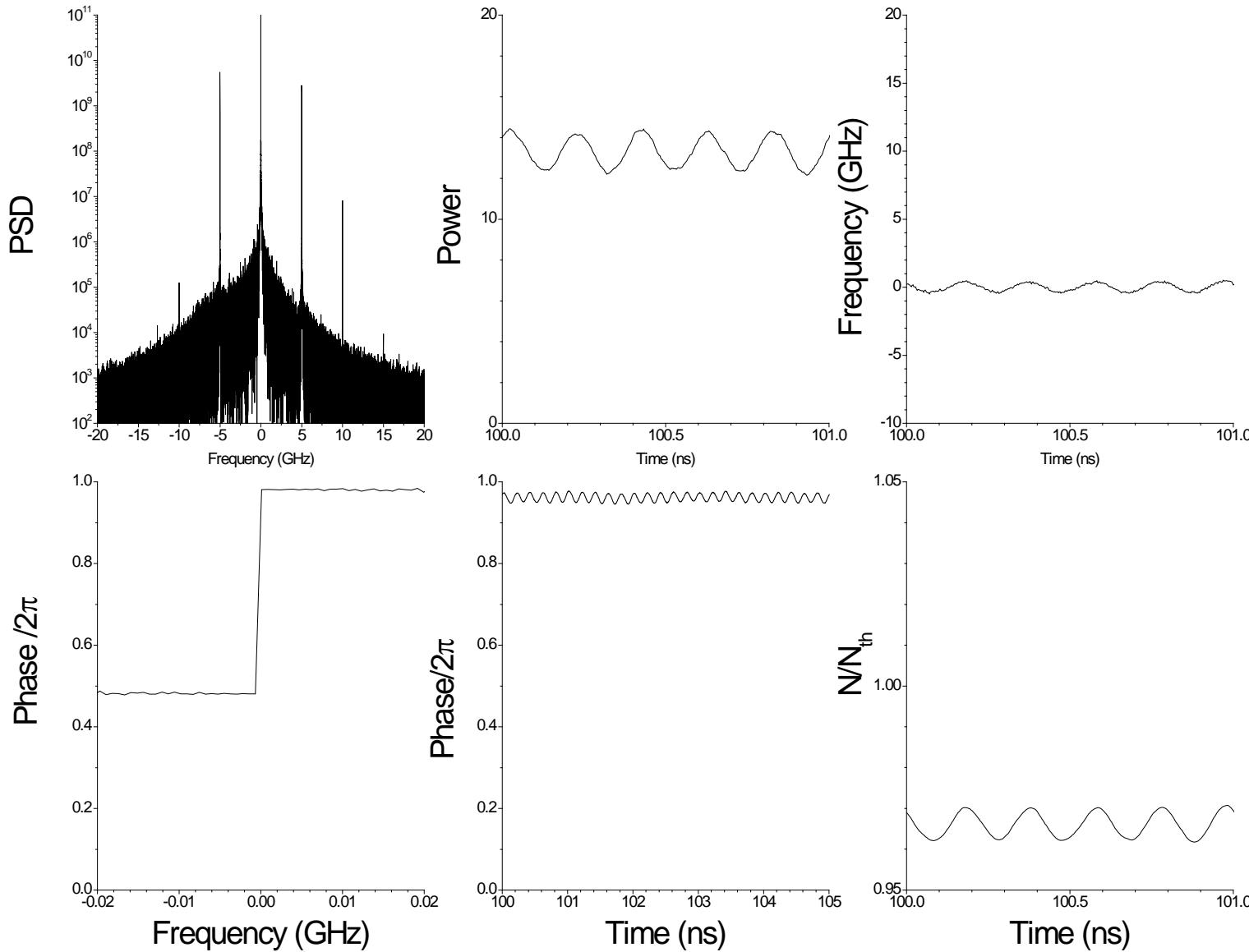
$$E(t) = A_0 \exp(i\phi_0) + A_1 \exp(i(2\pi f_m t + \phi_1)) + A_{-1} \exp(i(-2\pi f_m t + \phi_{-1})) = A(t) \exp(i\phi(t))$$

$$A^2(t) = E(t)E^*(t) = A_0^2 + A_1^2 + A_{-1}^2 + 2 A_0 A_1 \cos(2\pi f_m t + \phi_1 - \phi_0) + 2 A_0 A_{-1} \cos(2\pi f_m t + \phi_0 - \phi_{-1}) + 2 A_{-1} A_1 \cos(4\pi f_m t + \phi_1 - \phi_{-1})$$

$$\tan \phi(t) = (A_0 \sin(\phi_0) + A_1 \sin(2\pi f_m t + \phi_1) + A_{-1} \sin(-2\pi f_m t + \phi_{-1})) / (A_0 \cos(\phi_0) + A_1 \cos(2\pi f_m t + \phi_1) + A_{-1} \cos(-2\pi f_m t + \phi_{-1}))$$

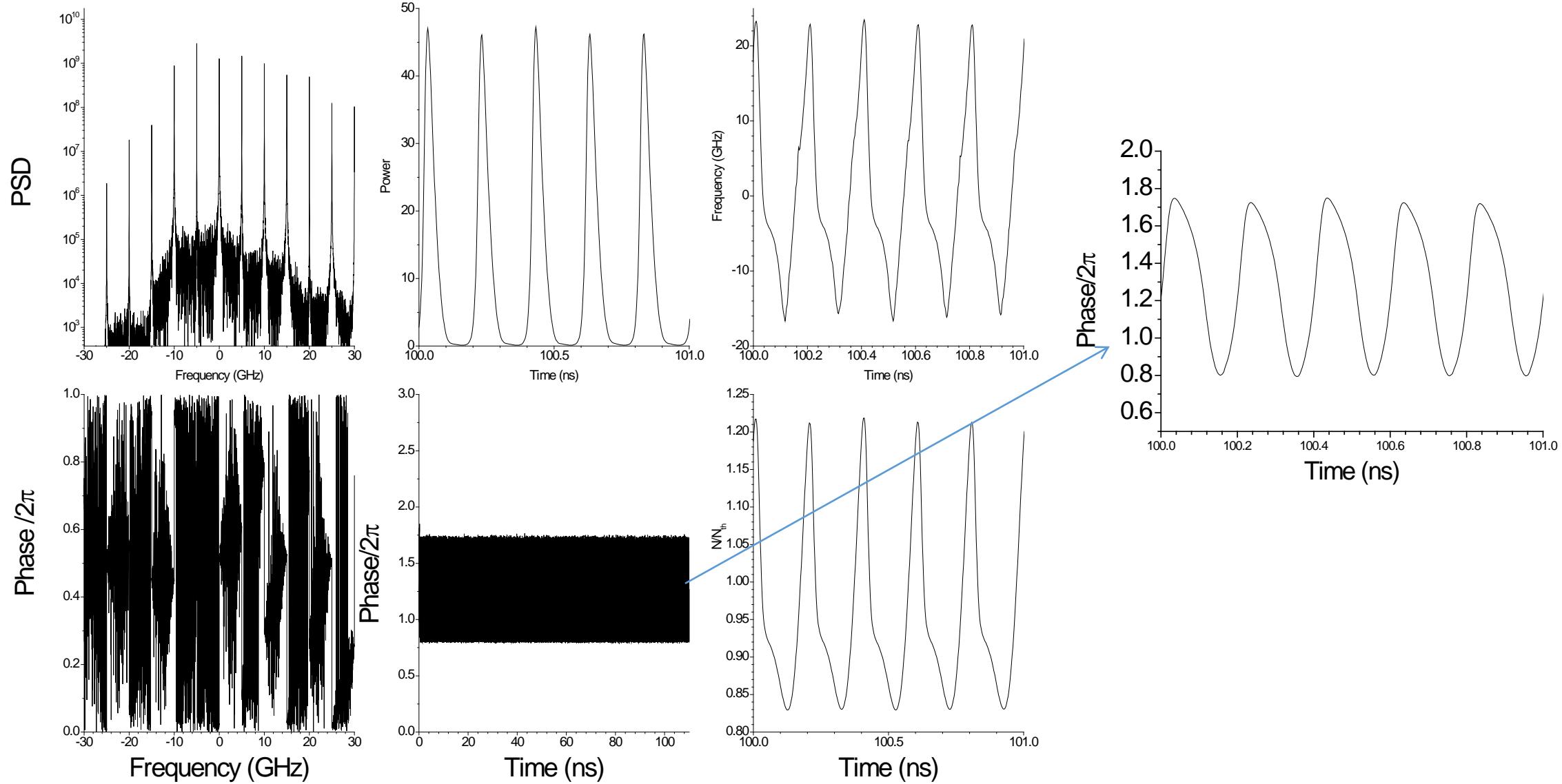
Optical Injection: YES. Detuning respect y-CW= -1.4 GHz,  $E_{\text{inj}}=0.5$ . Freqs referred to injection

Current Modulation: YES.  $m=0.05$ ,  $I_{\text{bias}}=11.5$  mA,  $f_{\text{mod}}=5$ GHz,  $tt=0.001$  ps, window=1310.72 ns

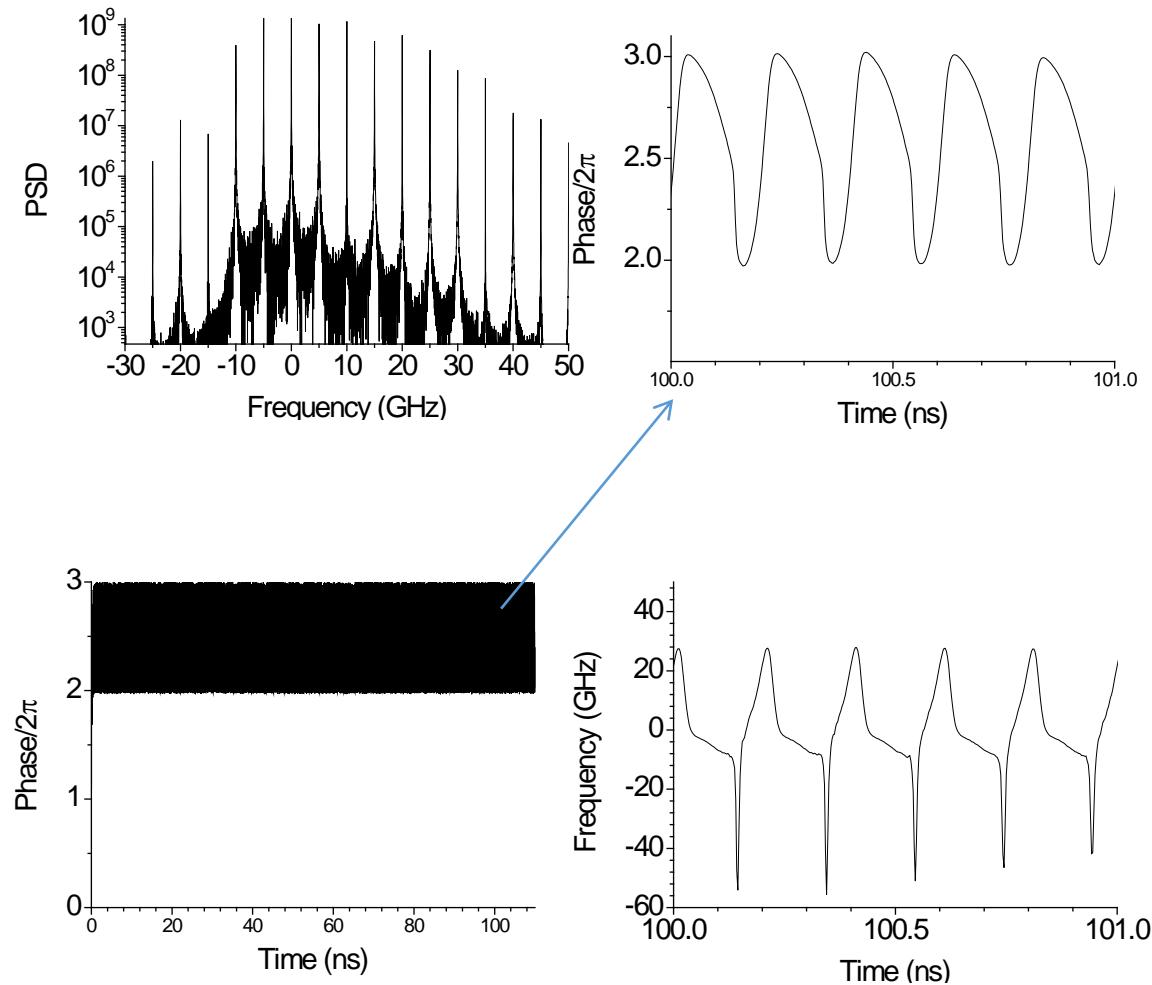


Optical Injection: YES. Detuning respect y-CW=-1.4 GHz,  $E_{\text{inj}}=0.5$ . Freqs referred to injection

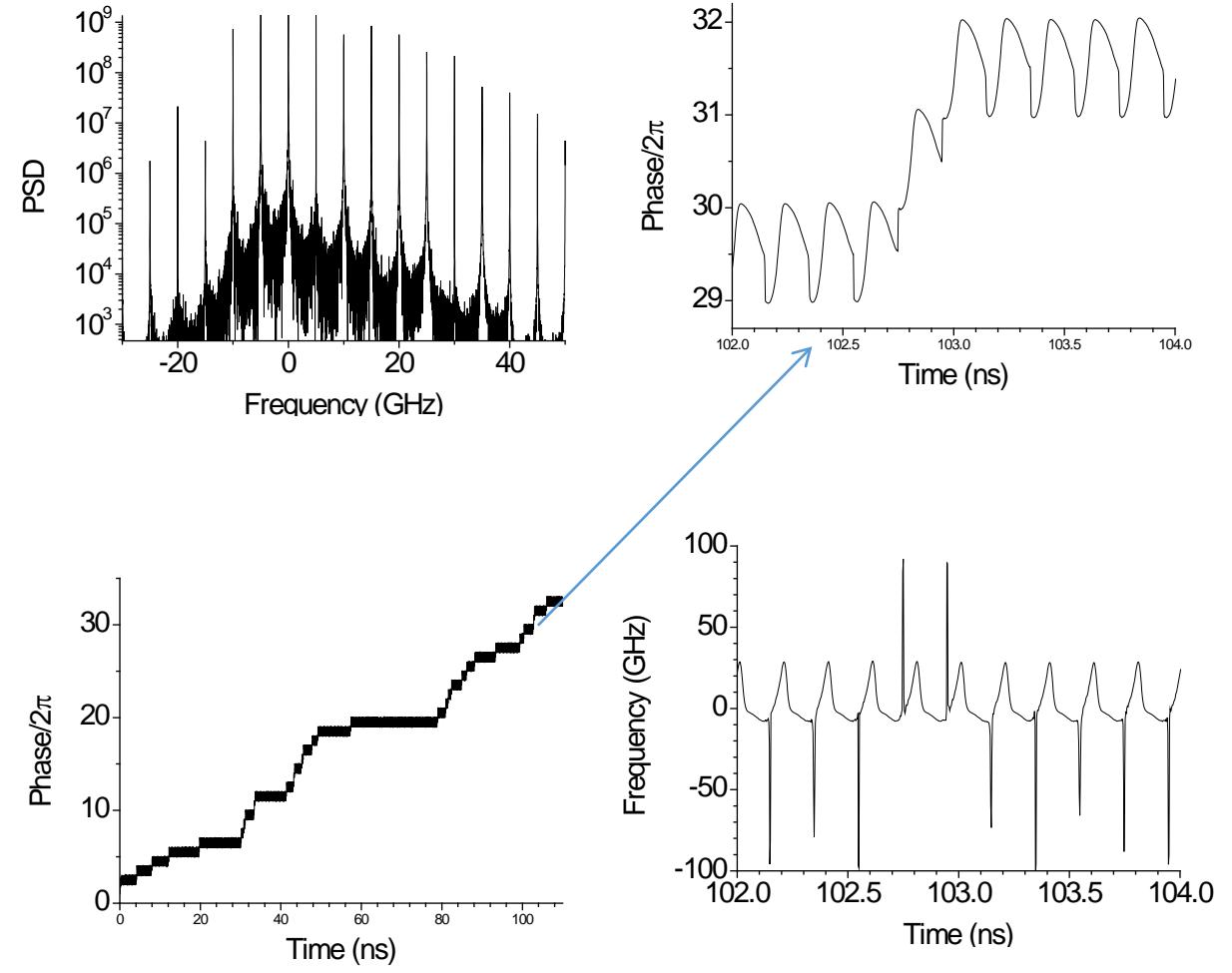
Current Modulation: YES.  $m=1.3$ ,  $I_{\text{bias}}=11.5 \text{ mA}$ ,  $f_{\text{mod}}=5 \text{ GHz}$



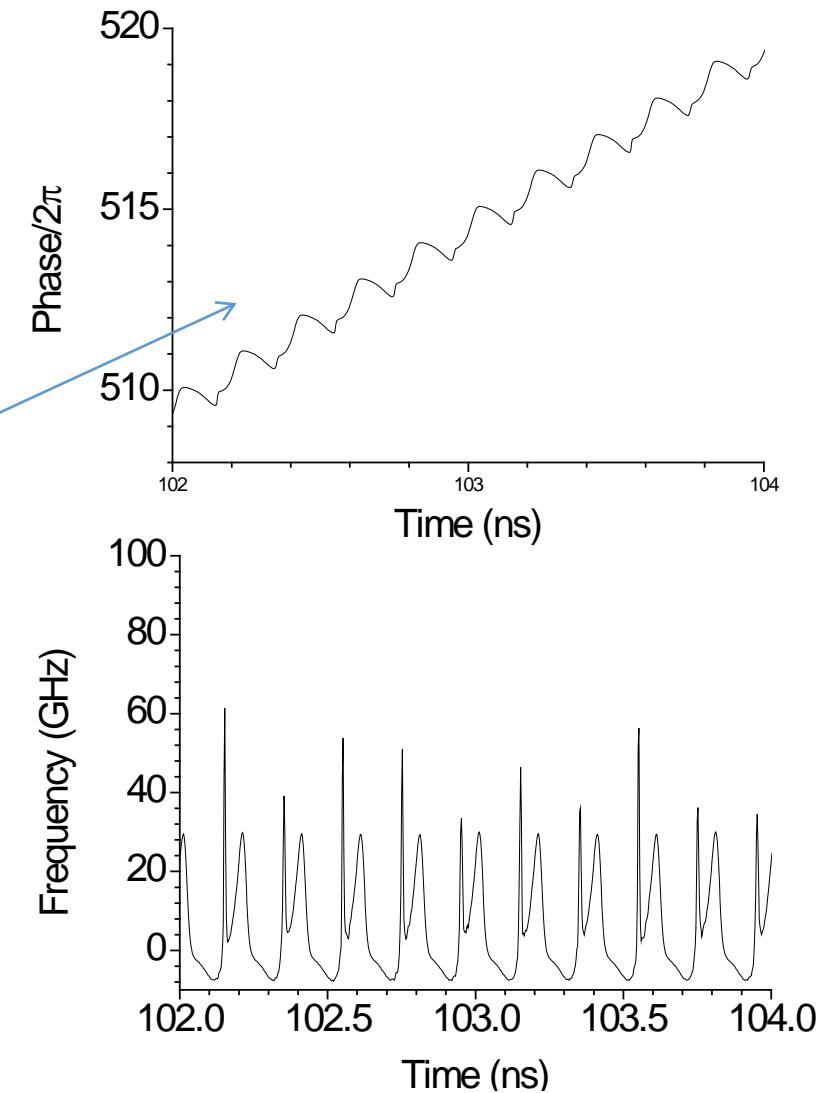
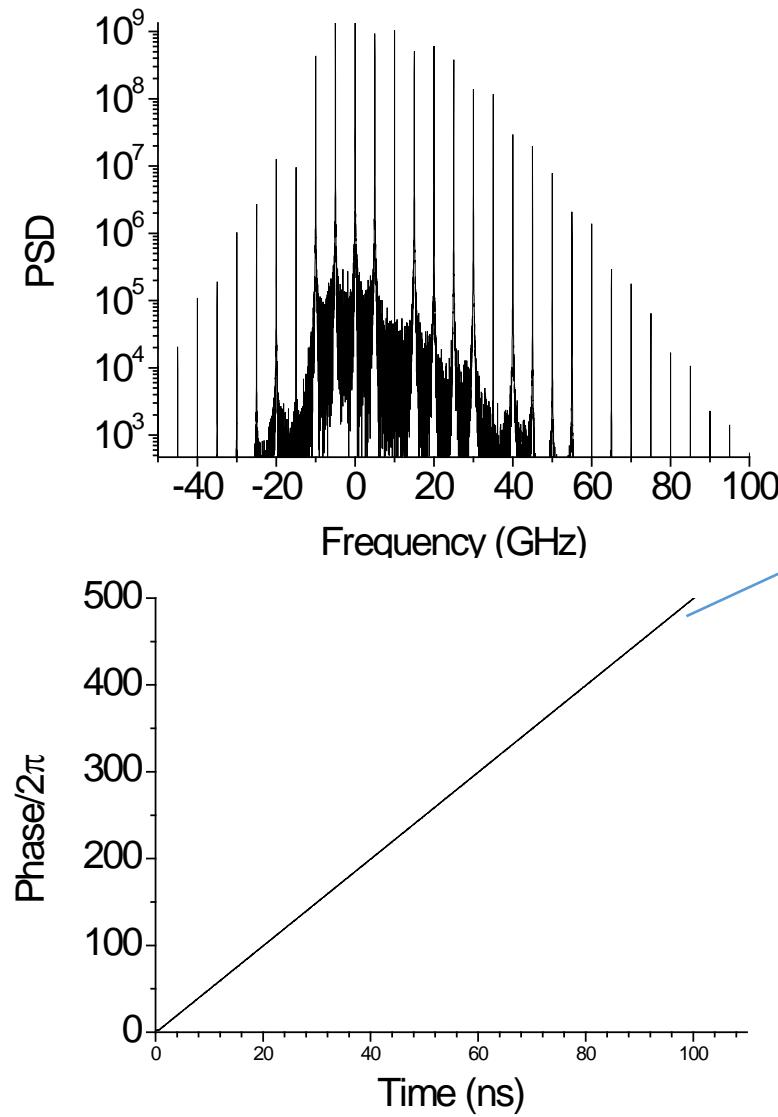
Detuning =-3.9 GHz



Detuning =-4.1 GHz

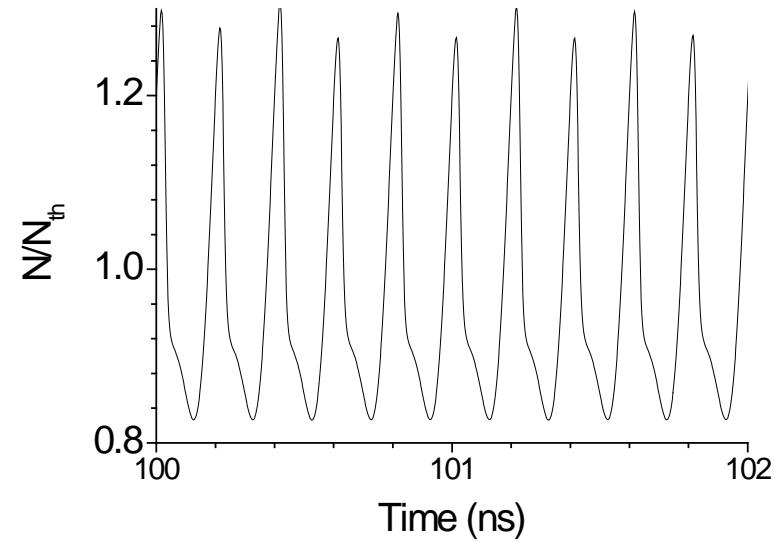
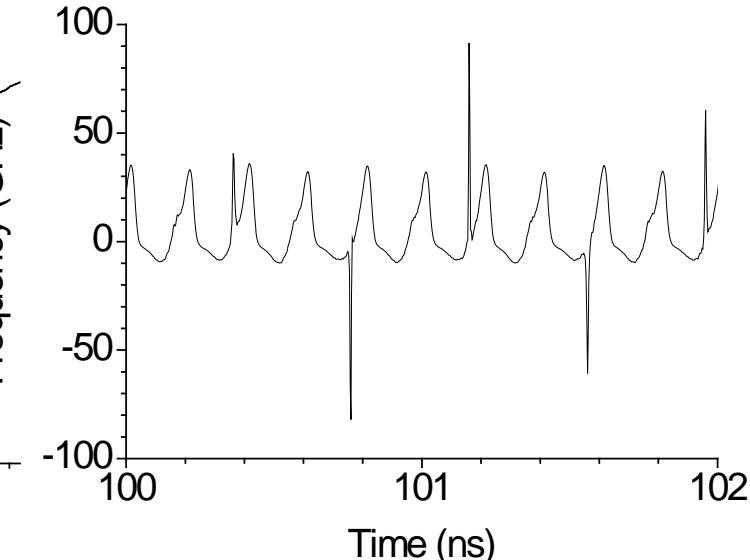
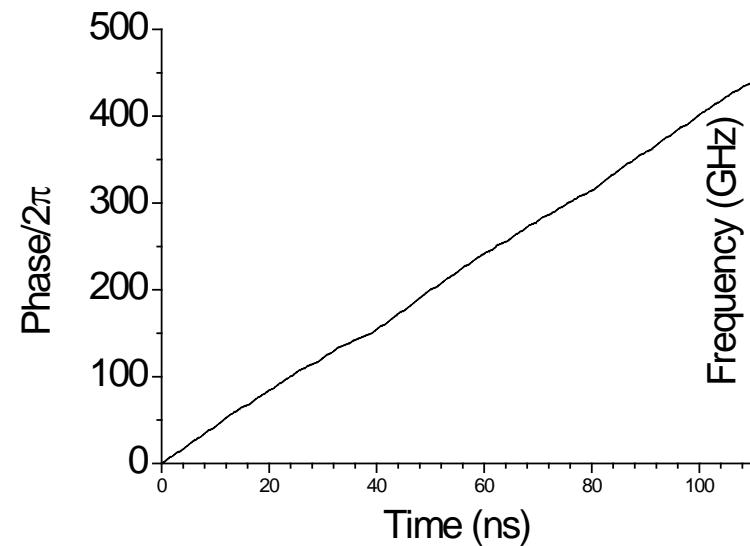
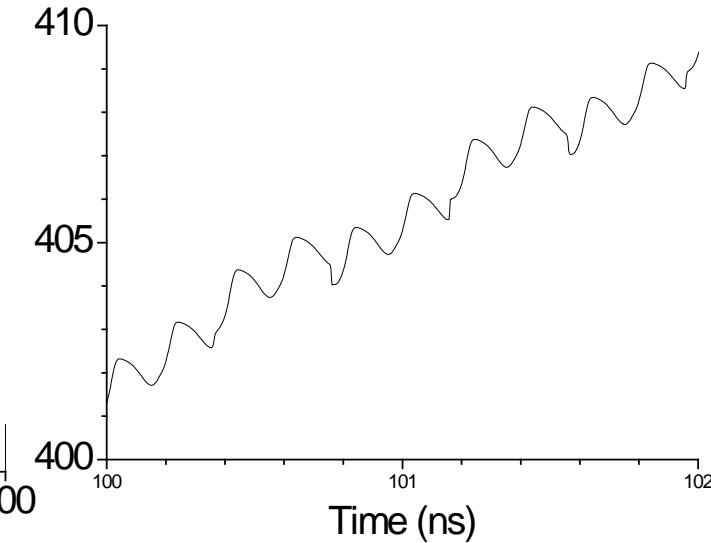
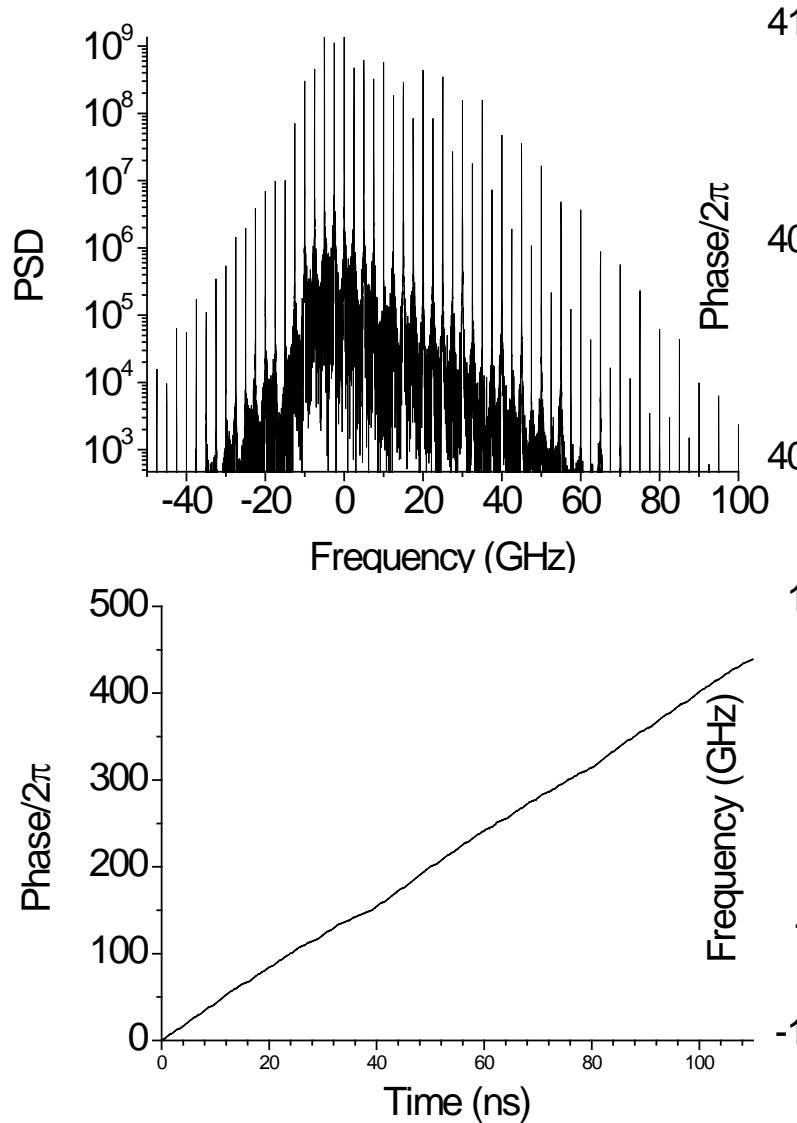


Detuning = -4.4 GHz,  $E_{\text{inj}}=0.5$



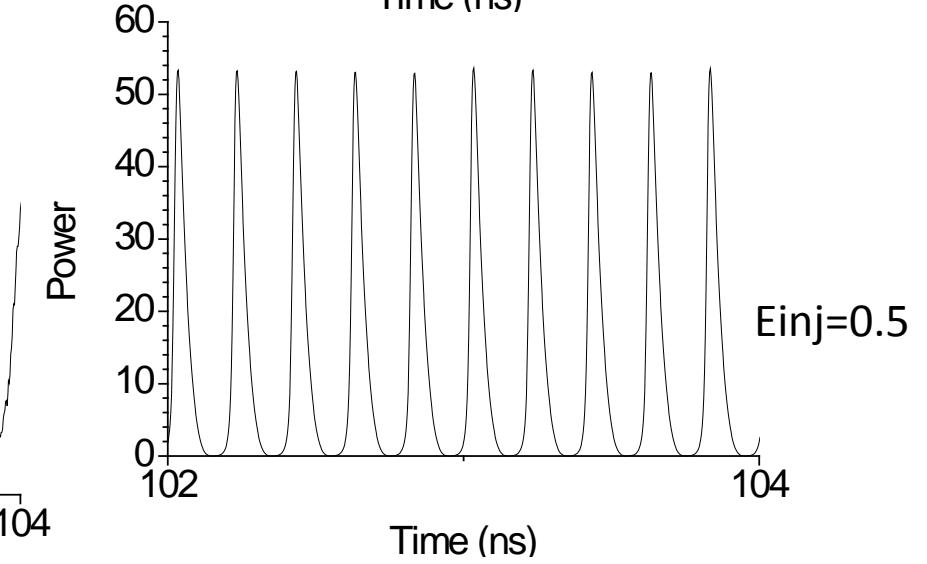
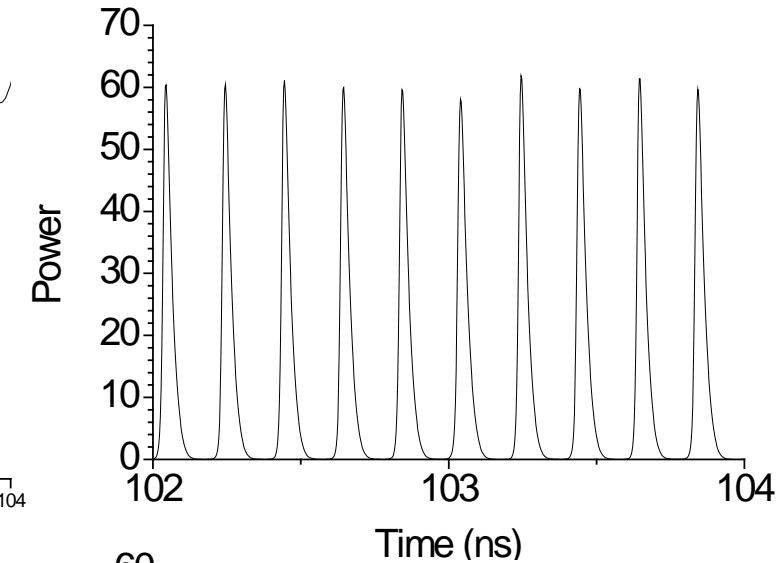
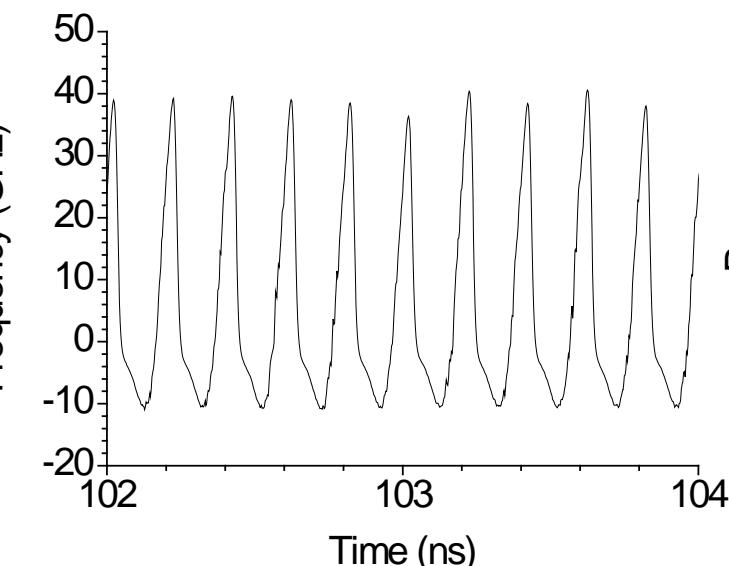
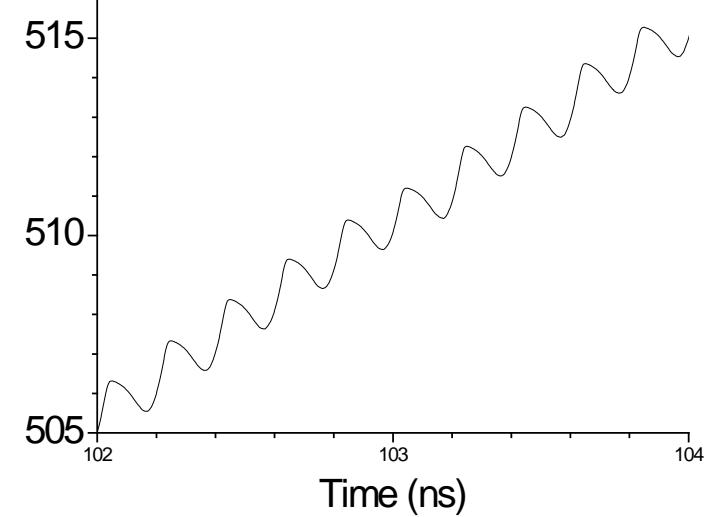
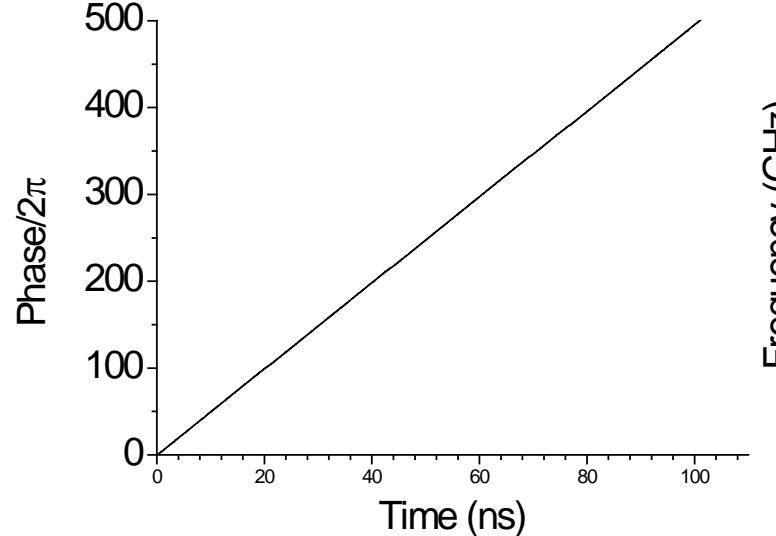
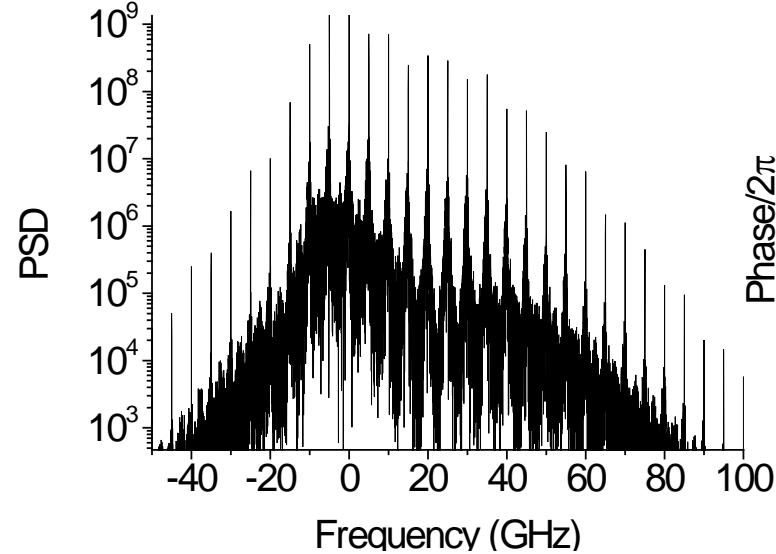
# 2T-locked

Detuning = -4.4 GHz,  $E_{\text{inj}} = 0.3$



# T-locked

Detuning = -4.4 GHz,  $E_{\text{inj}} = 0.04$





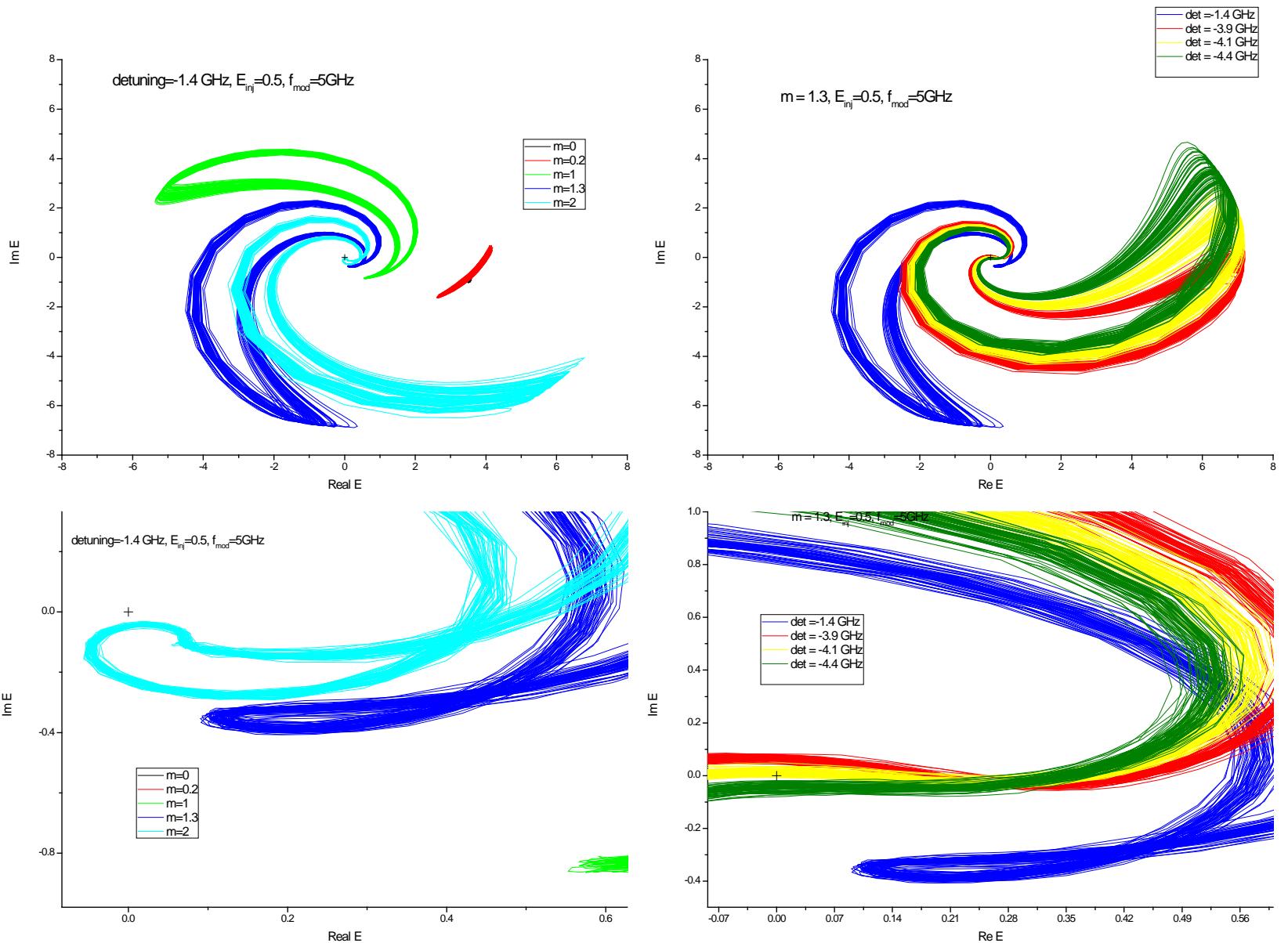
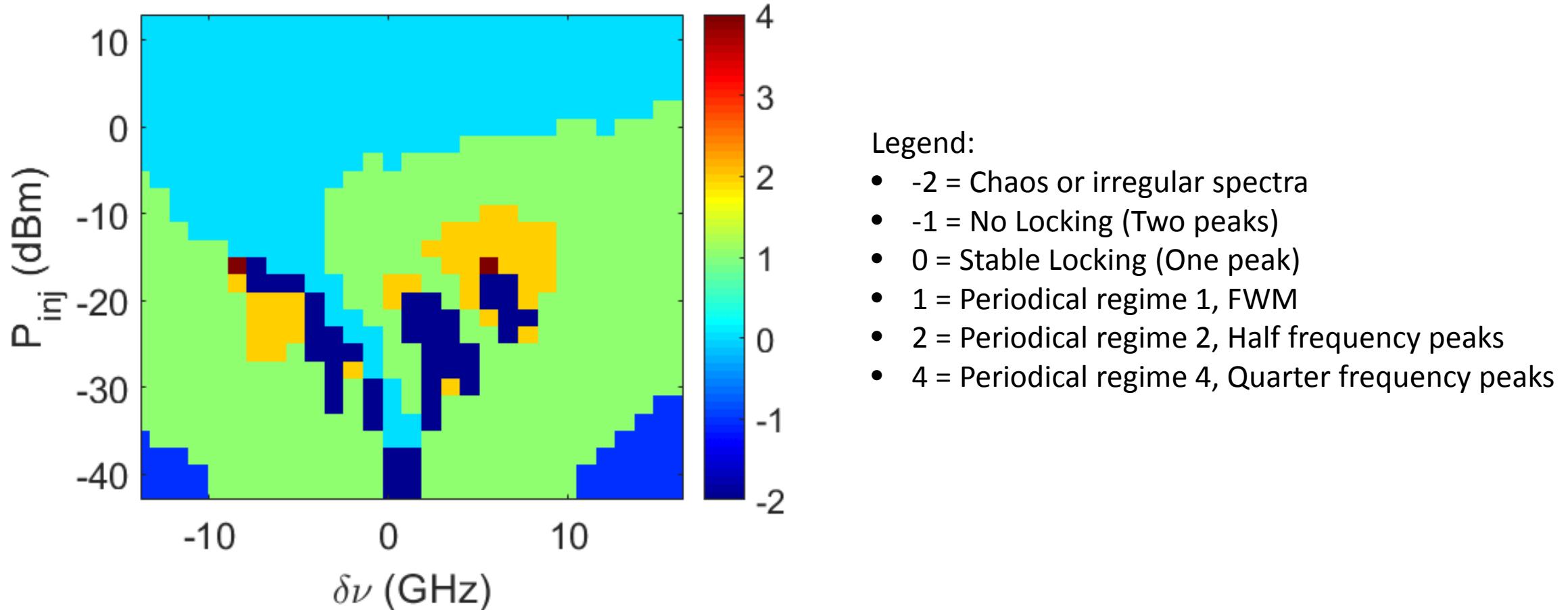


TABLE I  
VCSEL'S PARAMETER VALUES

Parameter	Meaning	Value
$\kappa$	<i>Field decay rate</i>	$36 \pm 3 \text{ ns}^{-1}$
$\gamma_a$	<i>Linear dichroism</i>	$5 \text{ ns}^{-1}$
$\gamma_p$	<i>Linear birefringence</i>	$106 \pm 1 \text{ ns}^{-1}$
$\alpha$	<i>Linewidth enhancement factor</i>	$2.1 \pm 0.3$
$\beta_{SF}$	<i>Spontaneous emission parameter</i>	$(5.4 \pm 1.7) \cdot 10^{-4}$
$\gamma$	<i>Decay rate of <math>D</math></i>	$2.8 \pm 0.3 \text{ ns}^{-1}$
$G_N$	<i>Differential gain</i>	$(3.37 \pm 0.09) \cdot 10^4 \text{ s}^{-1}$
$N_t$	<i>Carrier number at transparency</i>	$(1.49 \pm 0.03) \cdot 10^7$
$N_{th}$	<i>Carrier number at threshold</i>	$(1.70 \pm 0.03) \cdot 10^7$
$\gamma_s$	<i>Spin-flip relaxation rate</i>	$1000 \text{ ns}^{-1}$
$A$	<i>Nonradiative coefficient</i>	$2.1 \cdot 10^7 \text{ s}^{-1}$
$B$	<i>Radiative coefficient</i>	$(6.0 \pm 1.2) \cdot 10^7 \text{ s}^{-1}$
$C$	<i>Auger coefficient</i>	$(7 \pm 3) \cdot 10^6 \text{ s}^{-1}$

# CW Spectral Measurements:

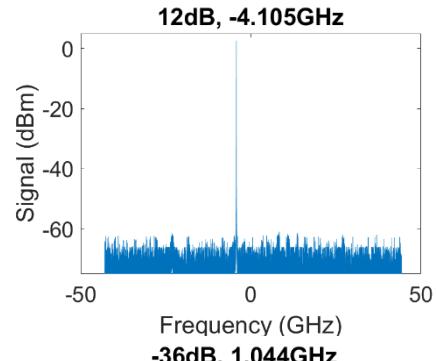
With External Injection, 21 mA



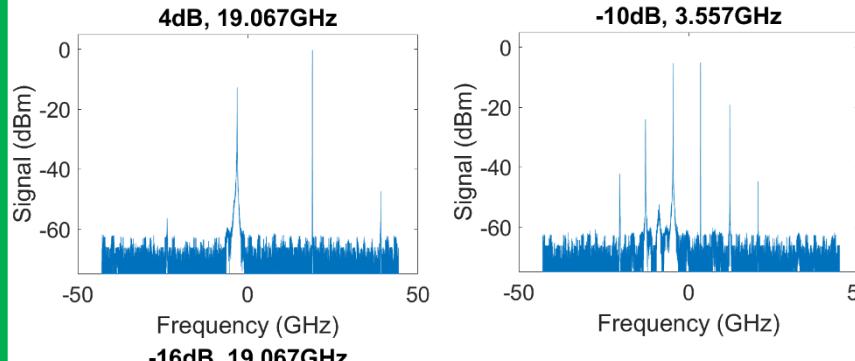
# CW Spectral Measurements:

With External Injection, 21 mA

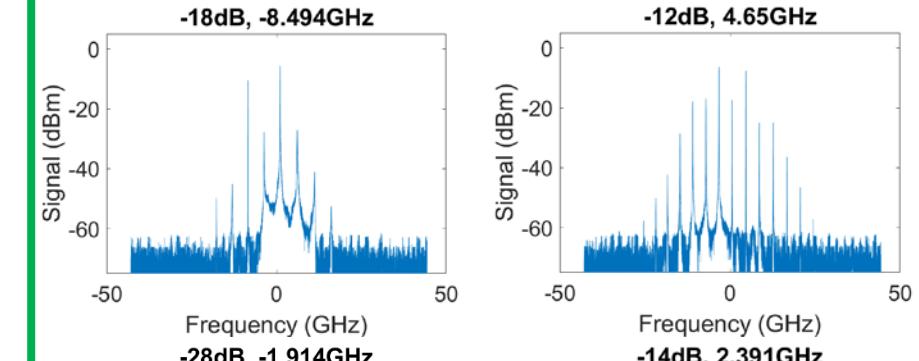
P0, Examples:



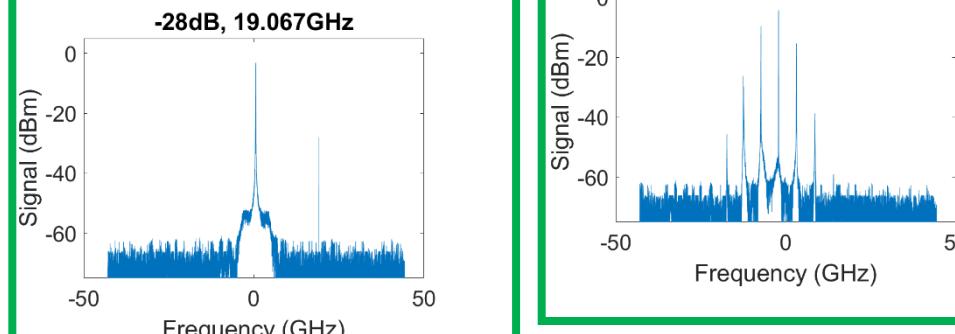
P1, Examples:



P2, Examples:



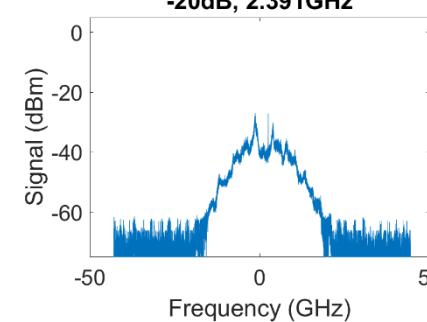
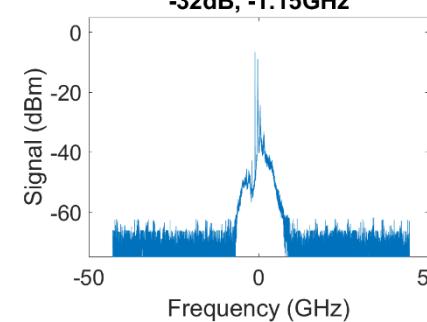
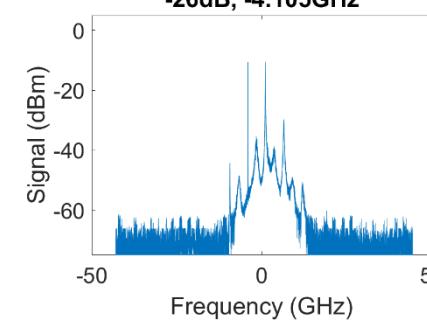
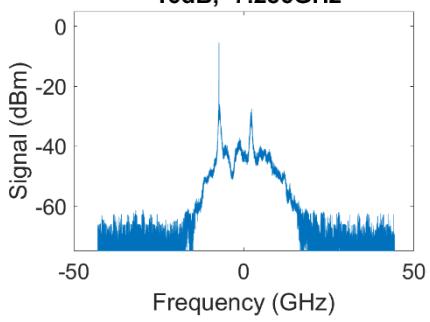
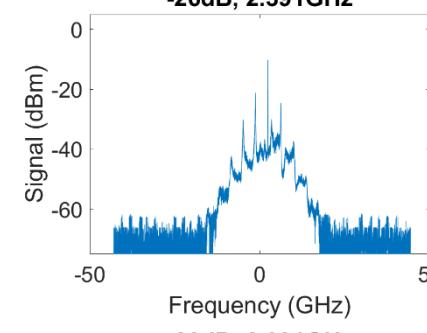
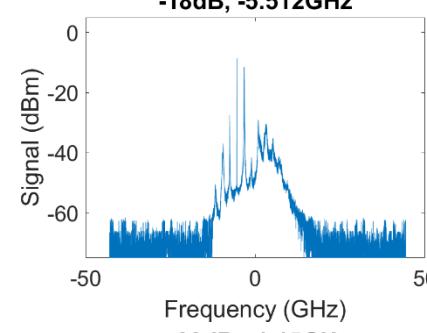
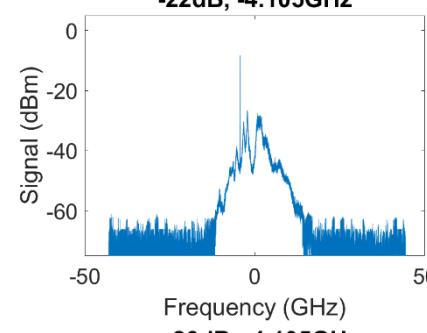
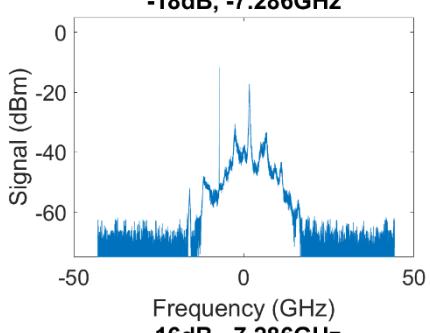
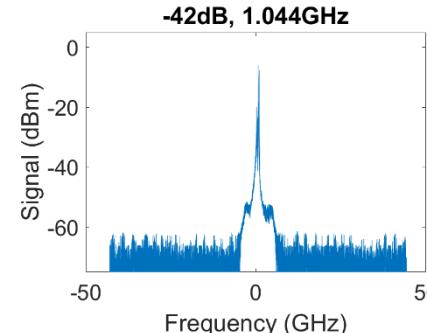
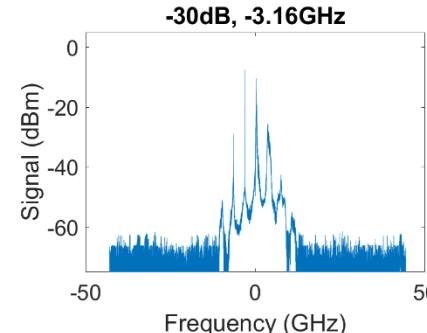
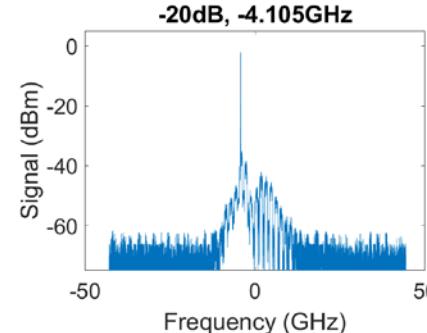
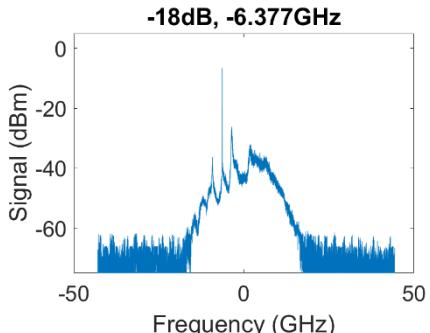
P(-1), Examples:



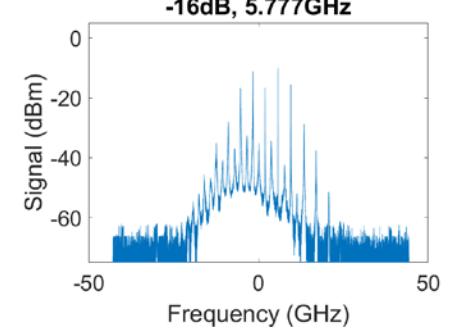
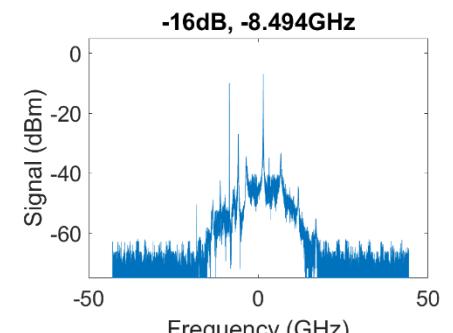
# CW Spectral Measurements:

## With External Injection, 21 mA

P(-2), Examples:

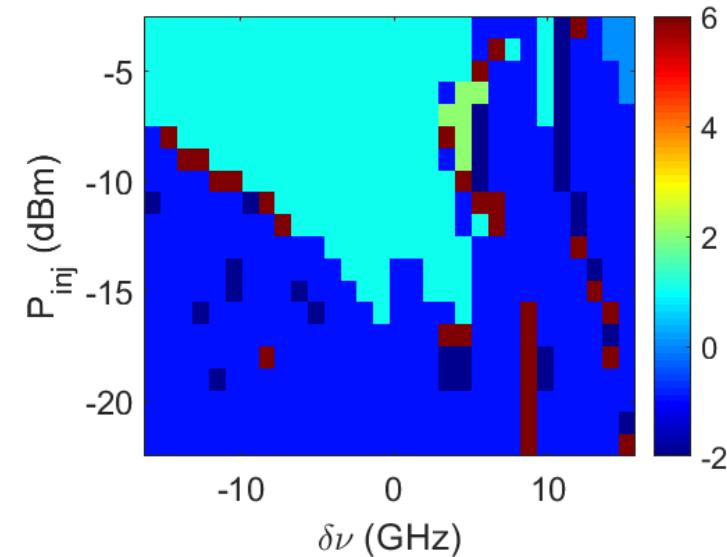
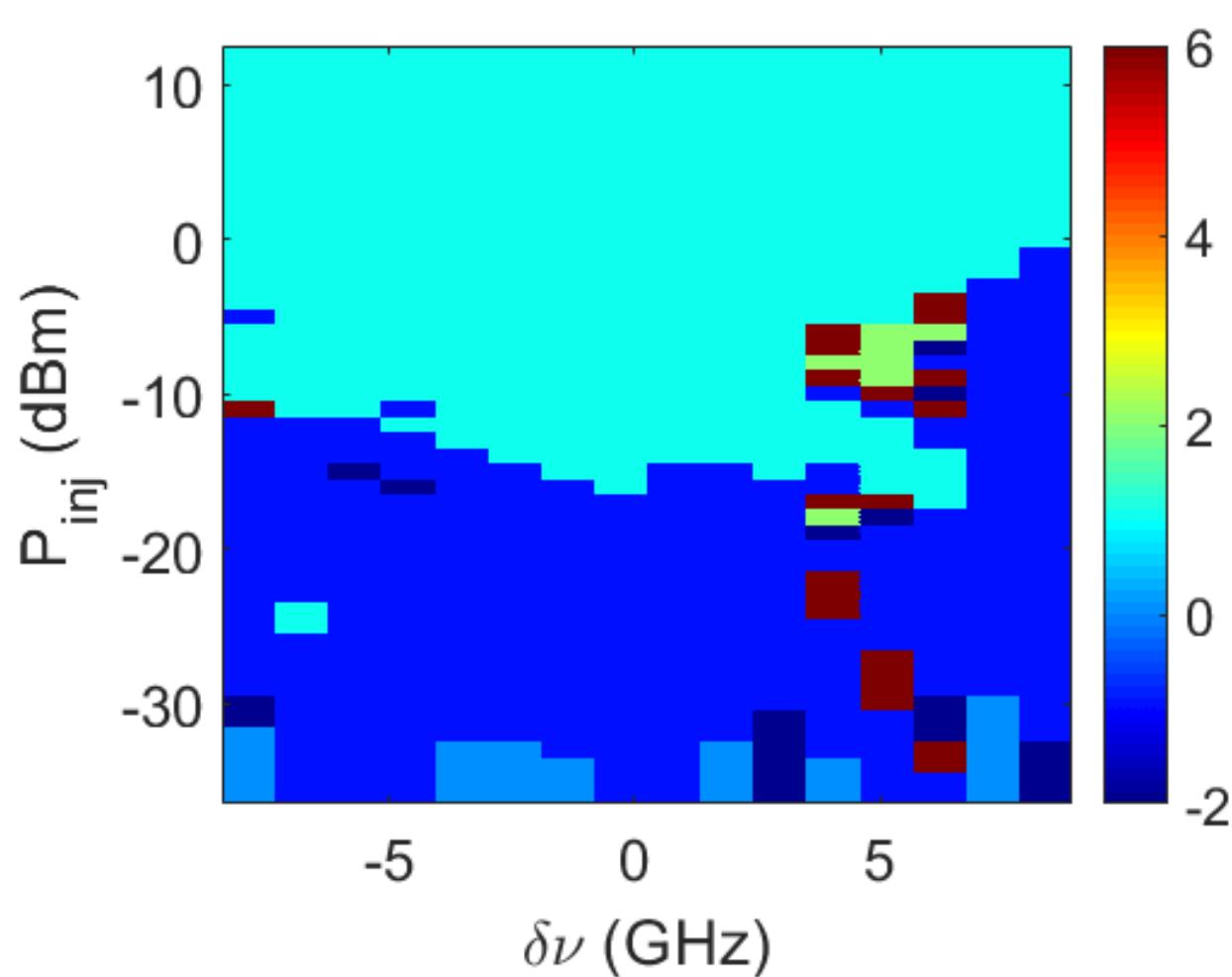


P4, Examples:



# CW Spectral Measurements:

With External Injection, 21 mA, 5GHz, 0.4 V

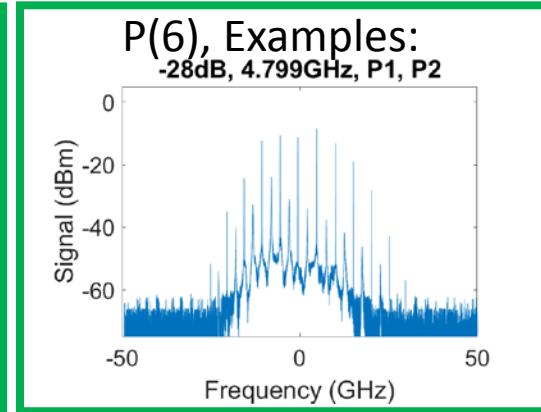
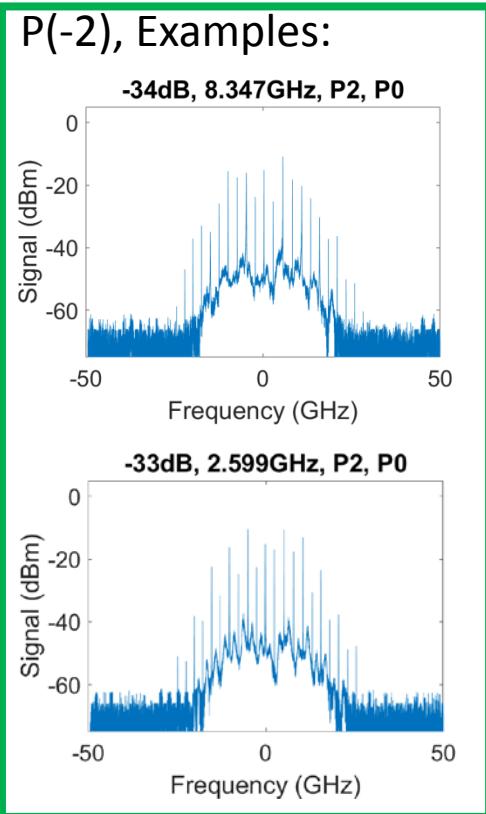
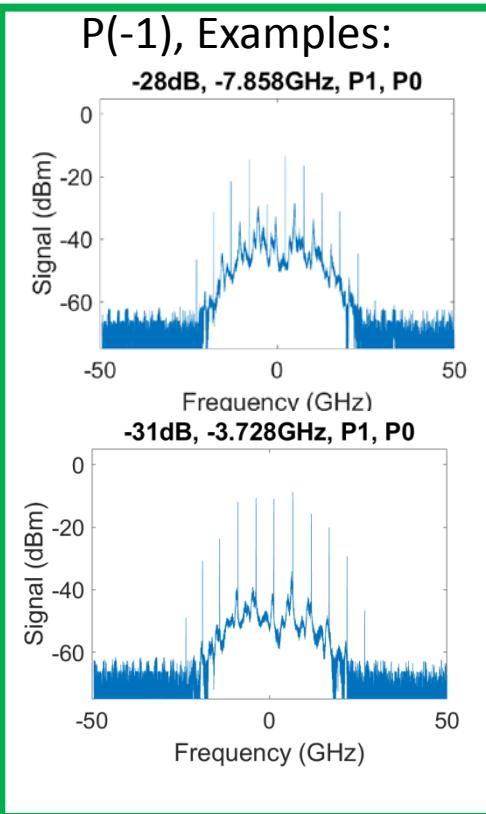
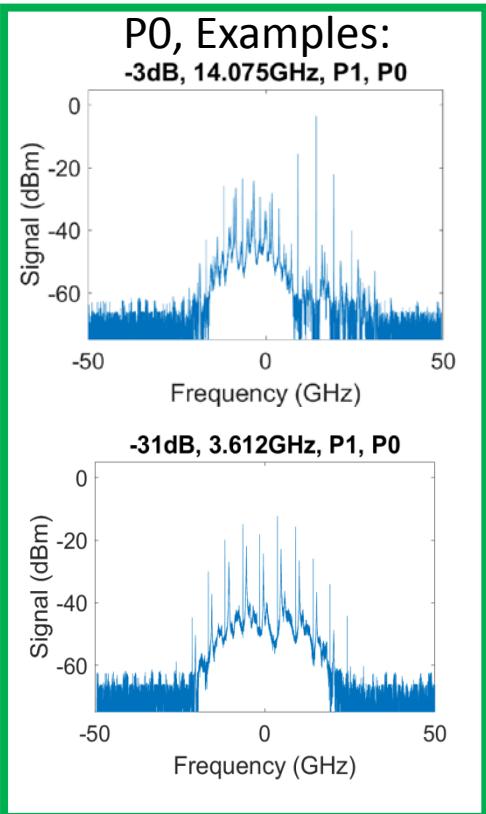


## Legend:

- -2 = P2, partial locking
- -1 = P1, partial locking
- 0 = No locking, FWM, Chaos
- 1 = P1, locked
- 2 = P2, locked
- 4 = P4, locked
- 6 = P1 (locked) + P2 (partially locked)

# CW Spectral Measurements:

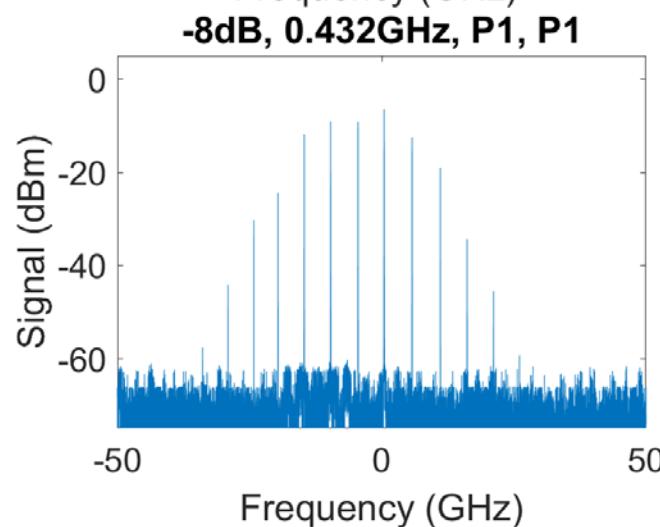
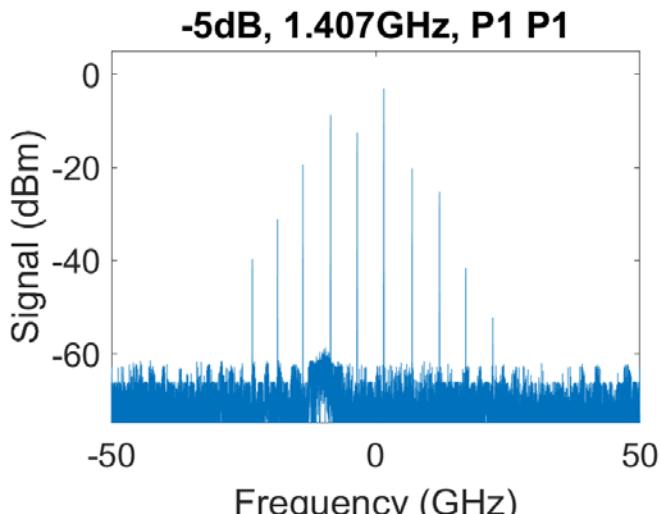
With External Injection, 21 mA, 5GHz, 0.4 V



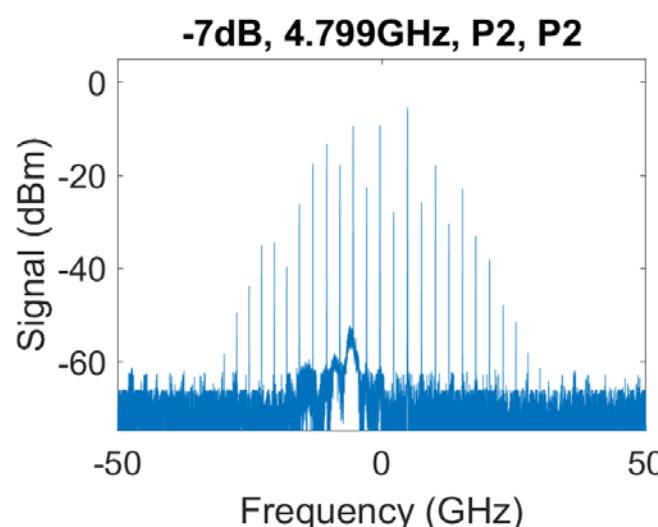
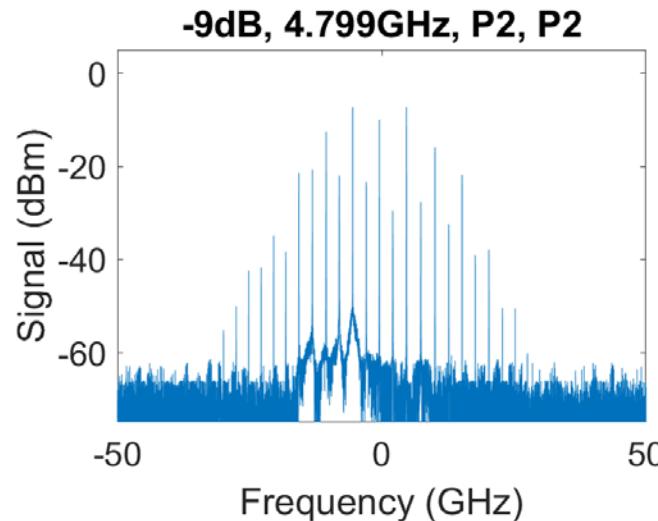
# CW Spectral Measurements:

With External Injection, 21 mA, 5GHz, 0.4 V

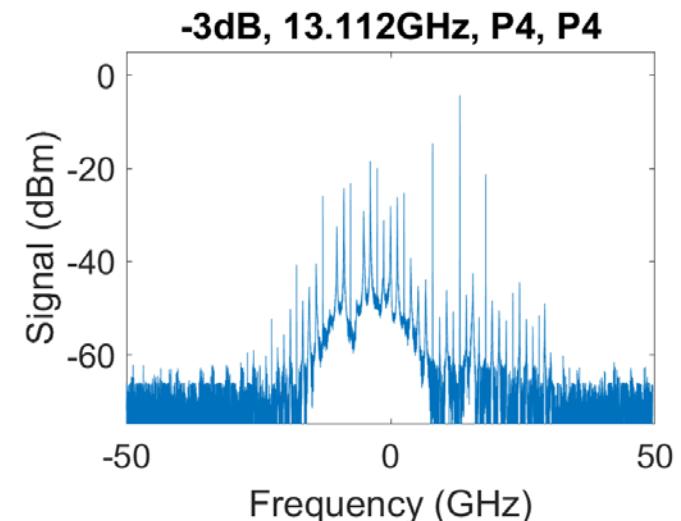
P1, Examples:



P2, Examples:

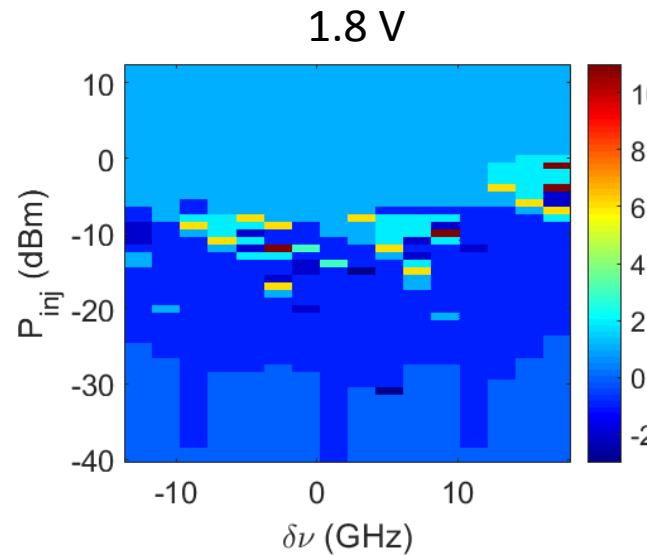
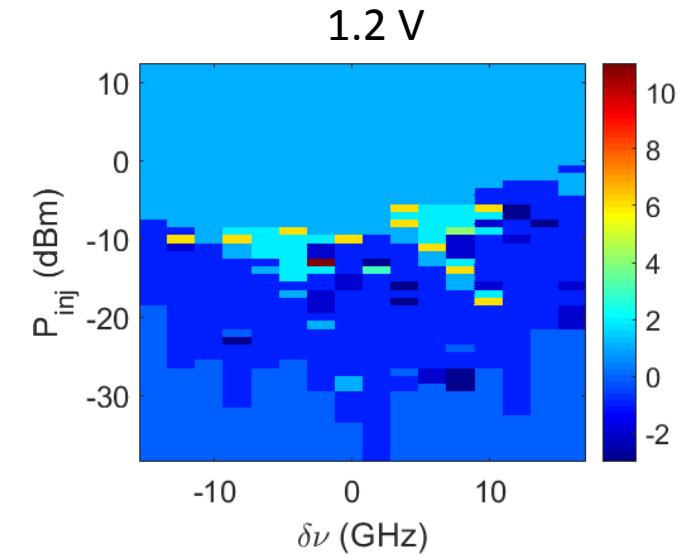
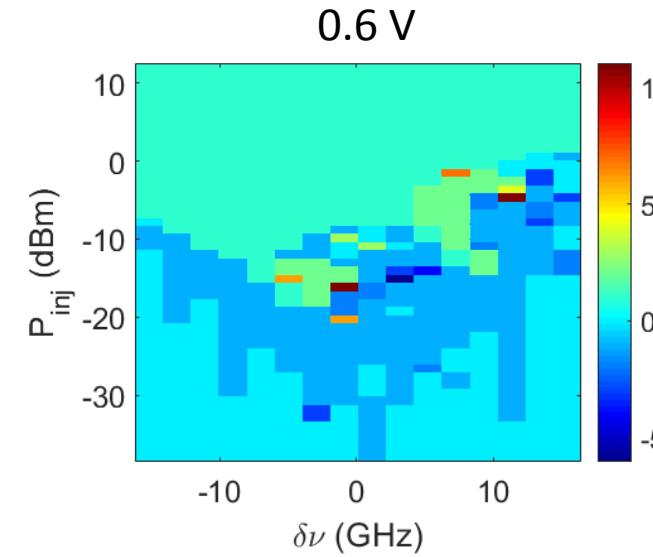
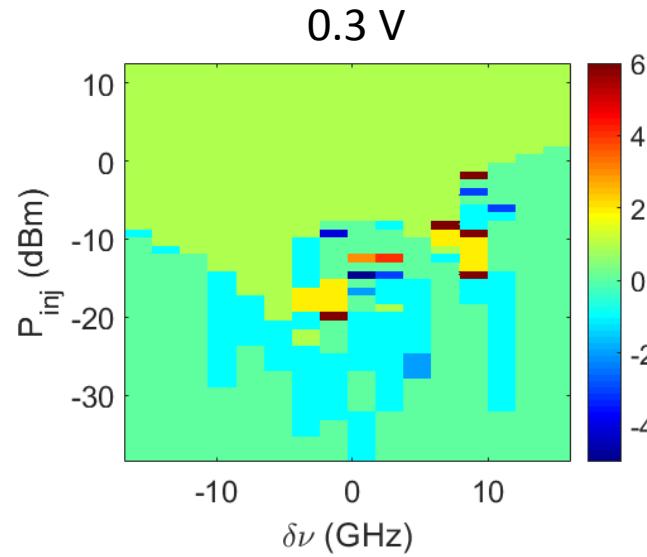


P4, Examples:



# CW Spectral Measurements:

With External Injection, 21 mA, 10GHz

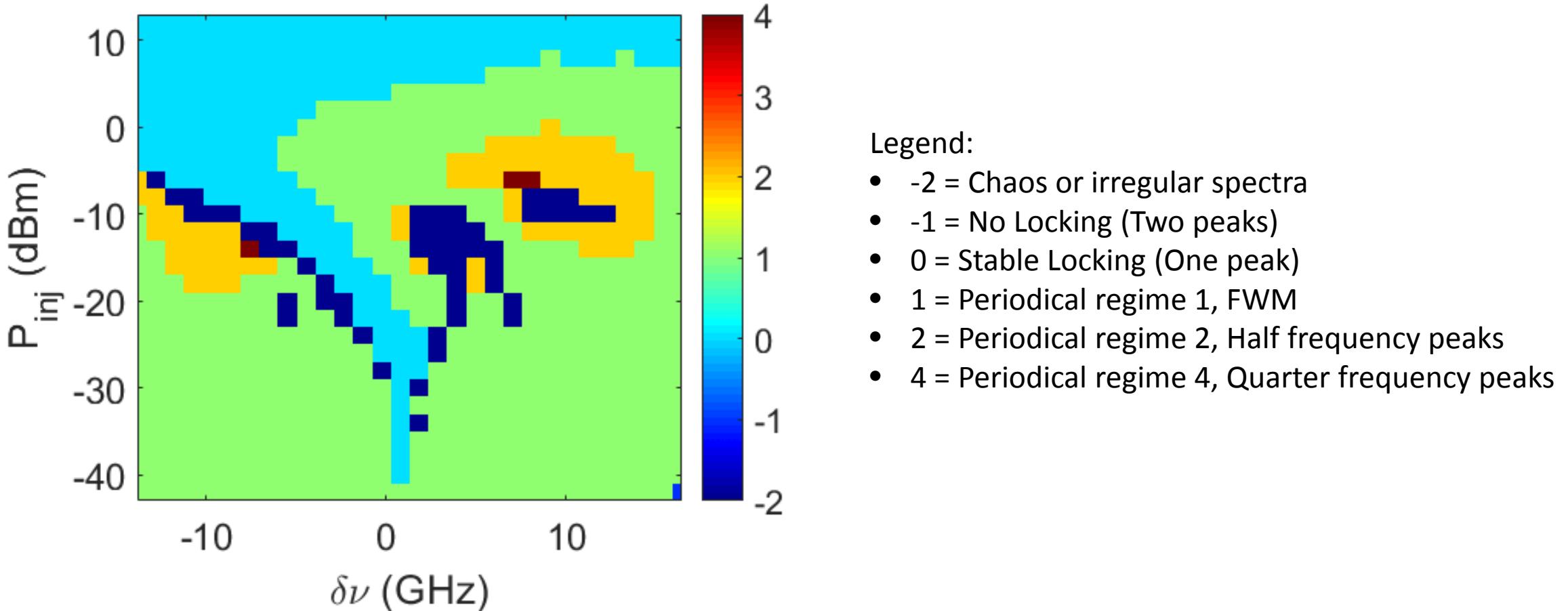


## Legend:

- -5 = P5, partial locking
- -4 = P4, partial locking
- -3 = P3, partial locking
- -2 = P2, partial locking
- -1 = P1, partial locking
- 0 = No locking, FWM, Chaos
- 1 = P1, locked
- 2 = P2, locked
- 3 = P3, locked
- 4 = P4, locked
- 6 = P1 (locked) + P2 (partially locked)
- 11 = P2 (locked) + P4 (partially locked)

# CW Spectral Measurements:

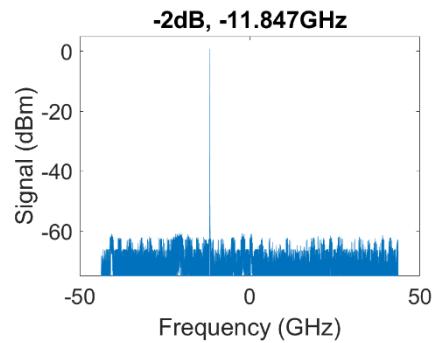
With External Injection, 32 mA



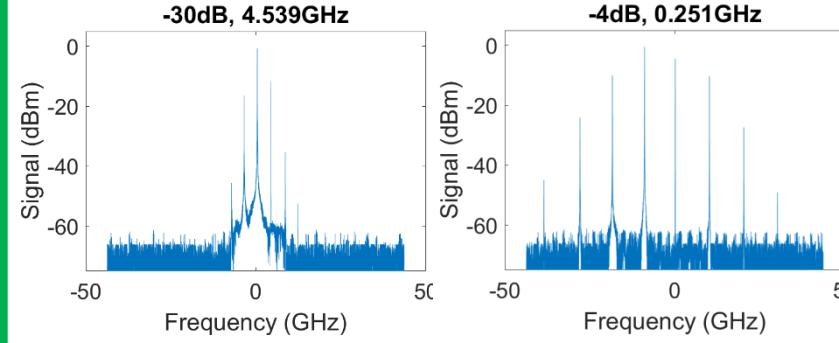
# CW Spectral Measurements:

With External Injection, 32 mA

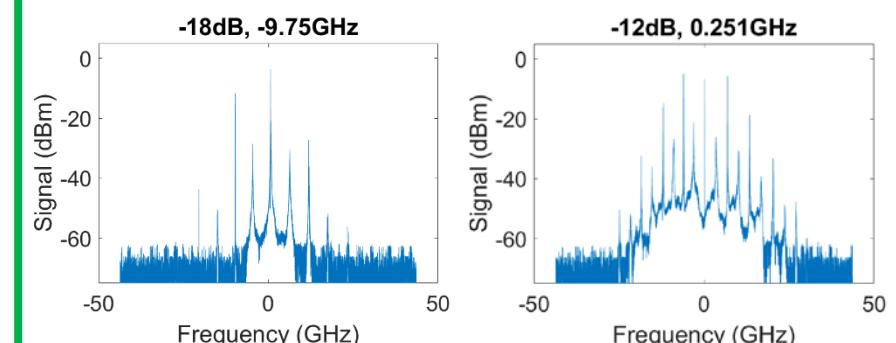
P0, Examples:



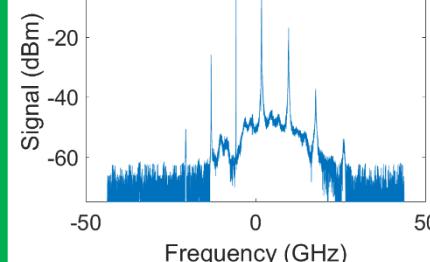
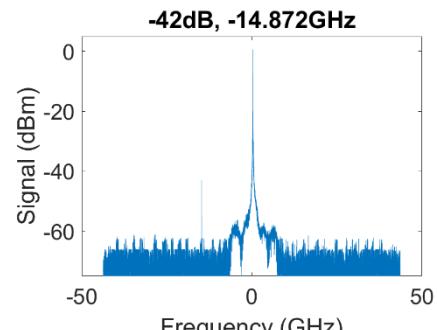
P1, Examples:



P2, Examples:



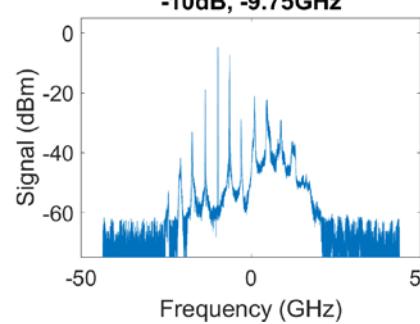
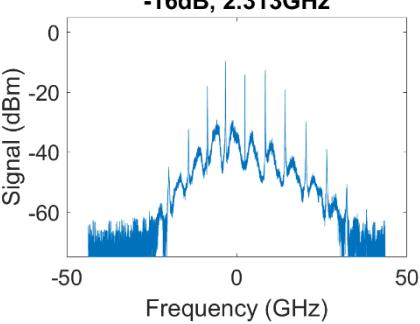
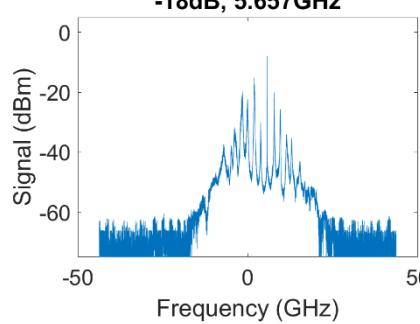
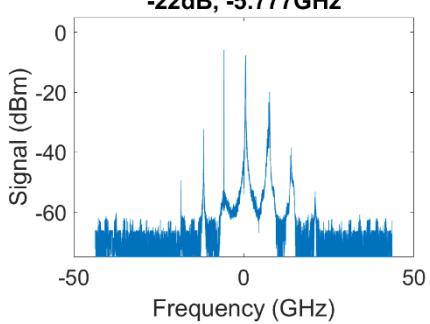
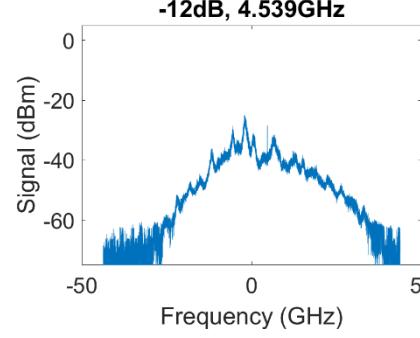
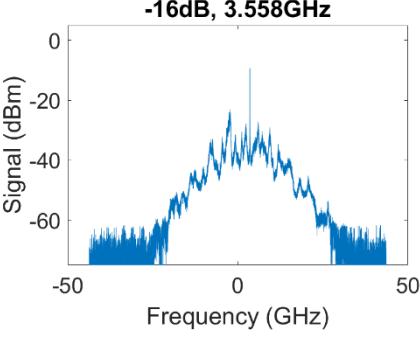
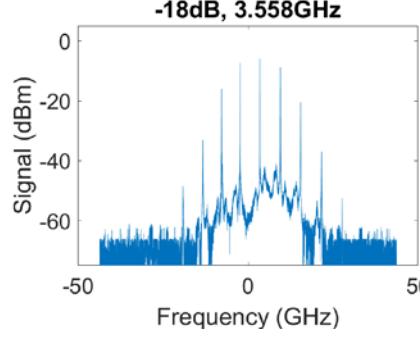
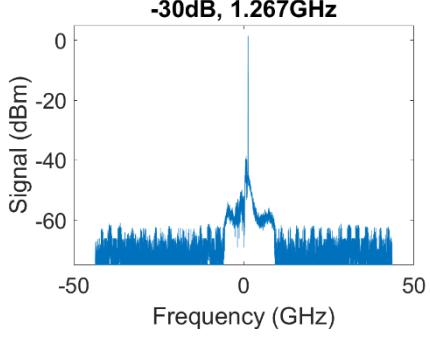
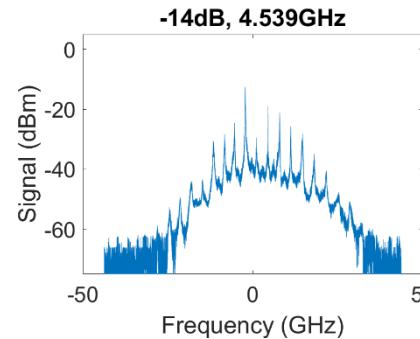
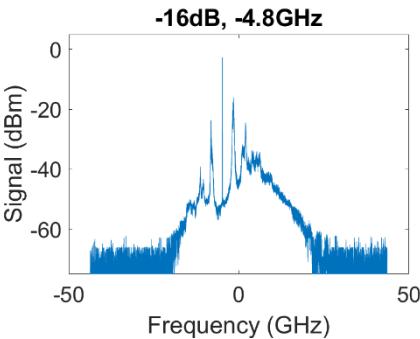
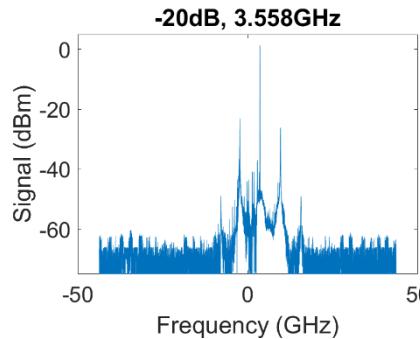
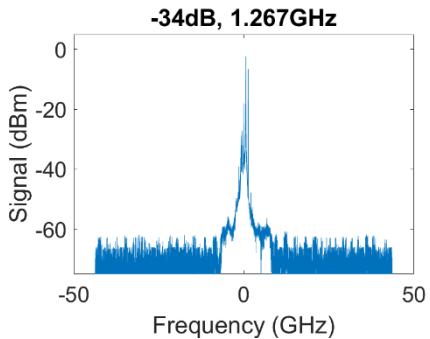
P(-1), Examples:



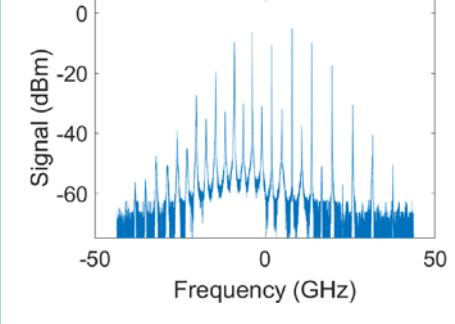
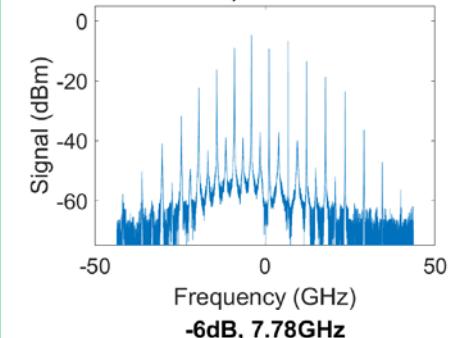
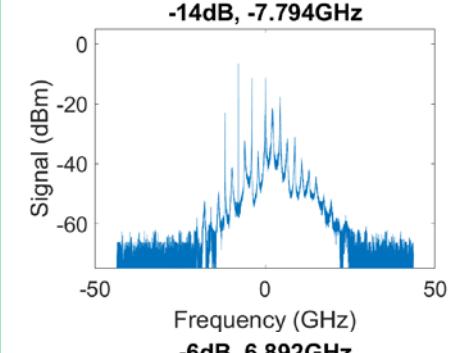
# CW Spectral Measurements:

## With External Injection, 32 mA

P(-2), Examples:

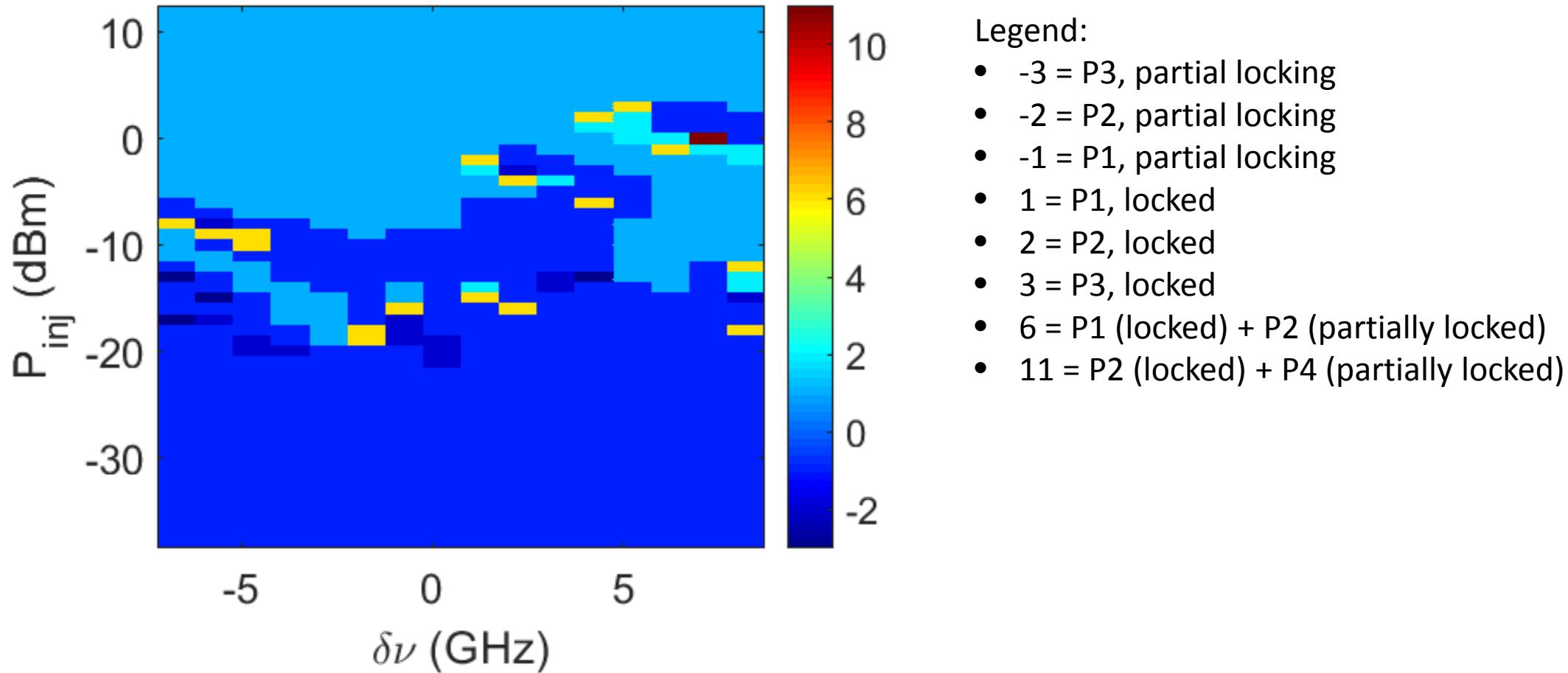


P4, Examples:



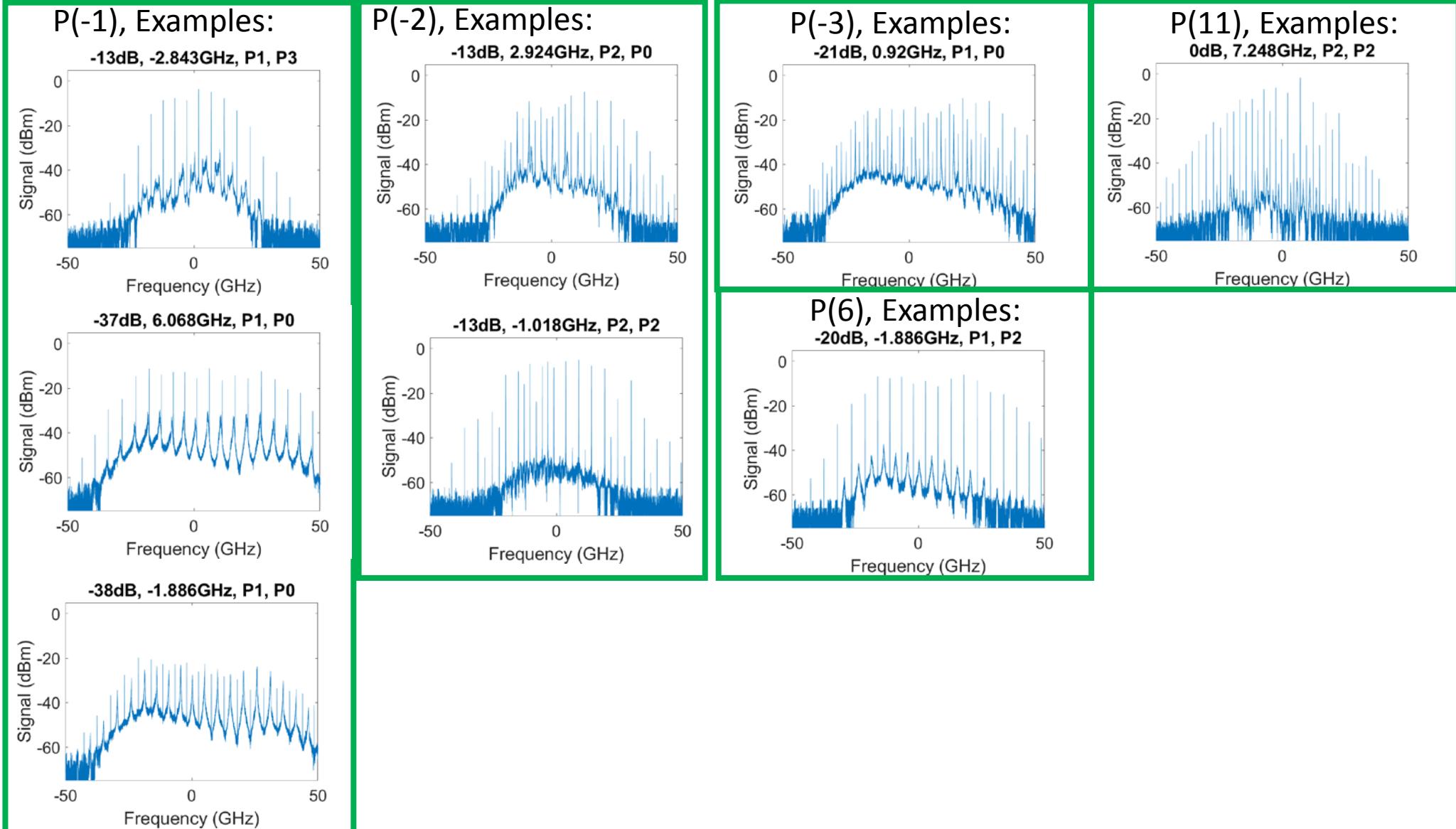
# CW Spectral Measurements:

With External Injection, 32 mA, 5GHz, 1 V



# CW Spectral Measurements:

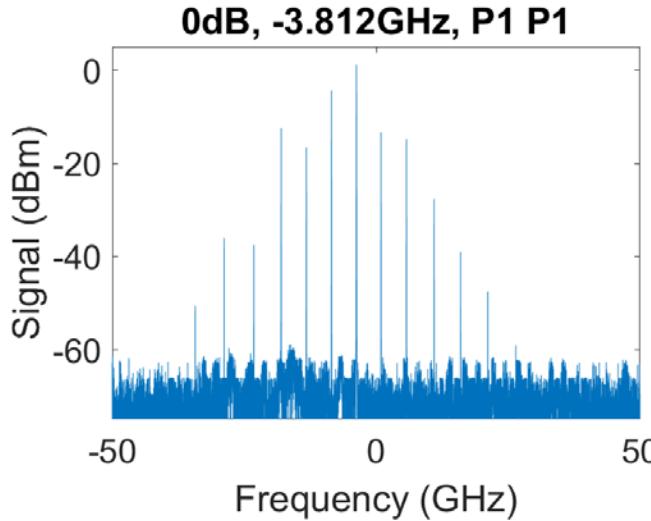
With External Injection, 32 mA, 5GHz, 1 V



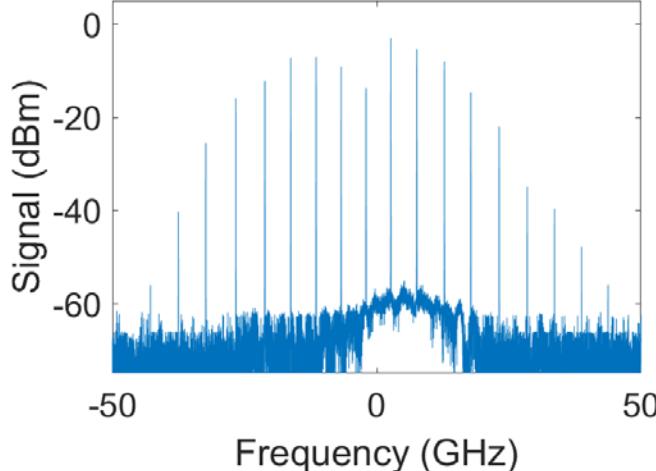
# CW Spectral Measurements:

With External Injection, 32 mA, 5GHz, 1 V

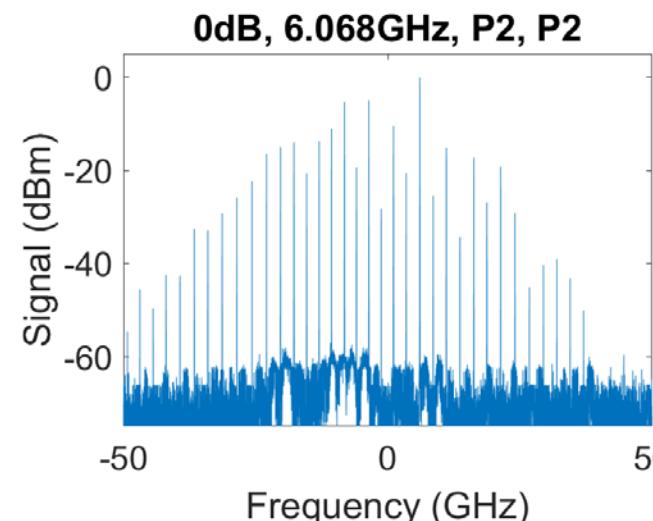
P1, Examples:



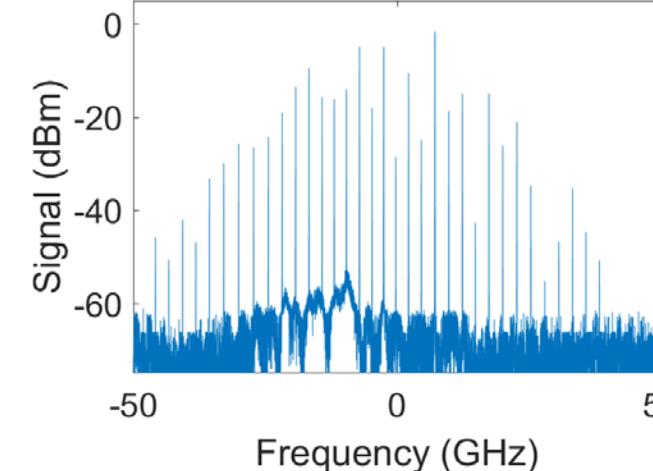
-10dB, -6.705GHz, P1 P1



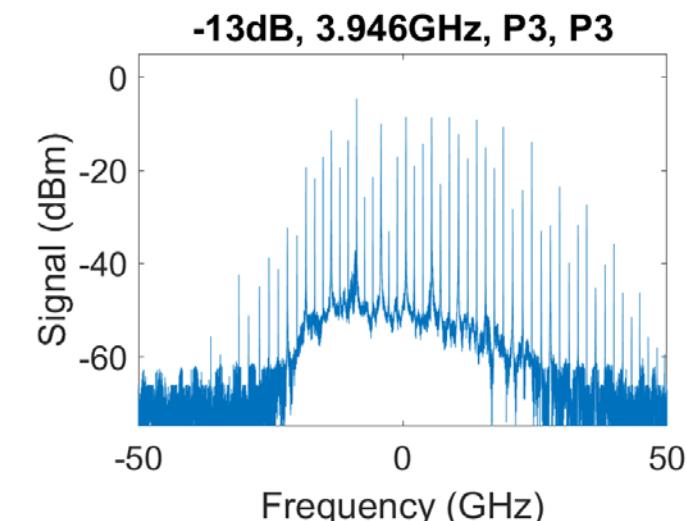
P2, Examples:



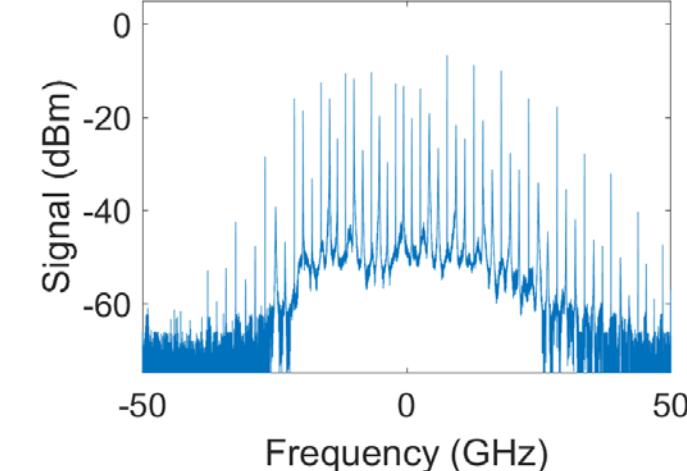
-1dB, 7.248GHz, P2, P2



P3, Examples:



-13dB, -6.705GHz, P3, P3



# CW Spectral Measurements:

With External Injection, 32 mA, 10 GHz, 1.2 V

