a. i. MNN configuration for token-encoded parametric oscillations

Token port

Output port

Ⓑ Ⓒ Ⓓ Linear waveguides' ports
Ⓐ Nonlinear waveguide's port
Coupling switch on chip (in use)

ii. Integrated circuit model for token-encoded parametric oscillations

Linear waveguide

Saturable Gain

Ⓑ 50 Ω

Ⓐ

Nonlinear waveguide

Token excitation

Coupler

Parametric Switches

Coupler

R_{bias} R_{bias}
V_{NL} V_{NL}
Supply

Linear waveguide

Ⓒ 50 Ω

Saturable Gain

Output

50 Ω Ⓓ
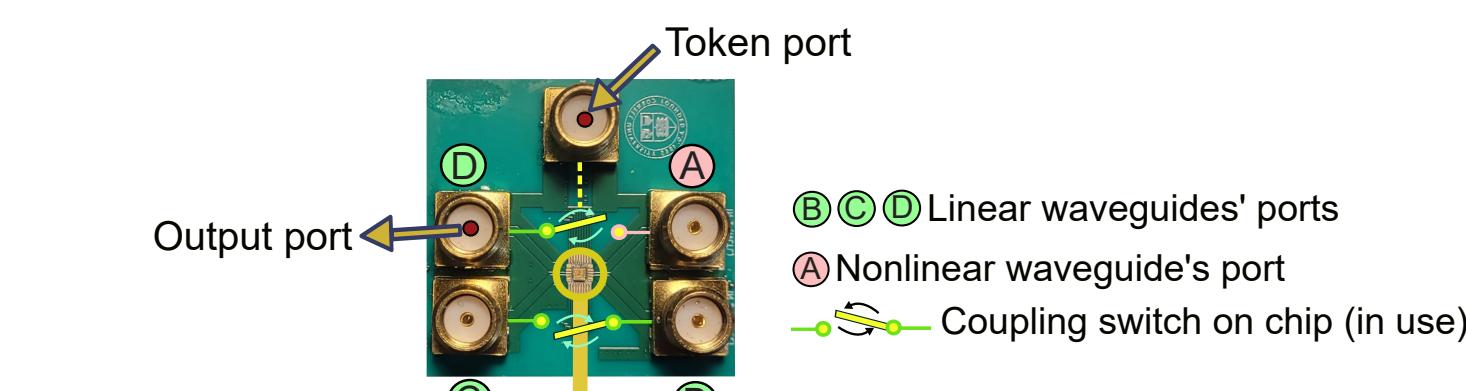
iii. Reduced circuit model for token-encoded parametric oscillations

$I_{sat_{NL}}$

L_{coup} V_{NL} L_{NL} L_{NL} L_{NL} L_{NL}

$C_{coup,2}$ $C_{S,par}$
$C_{coup,1}$ C_1 C_2 C_6

V_L $I_{sat_{lin}}$ V_{out}, I_{out}

L_{lin} C_{lin} 50 Ω
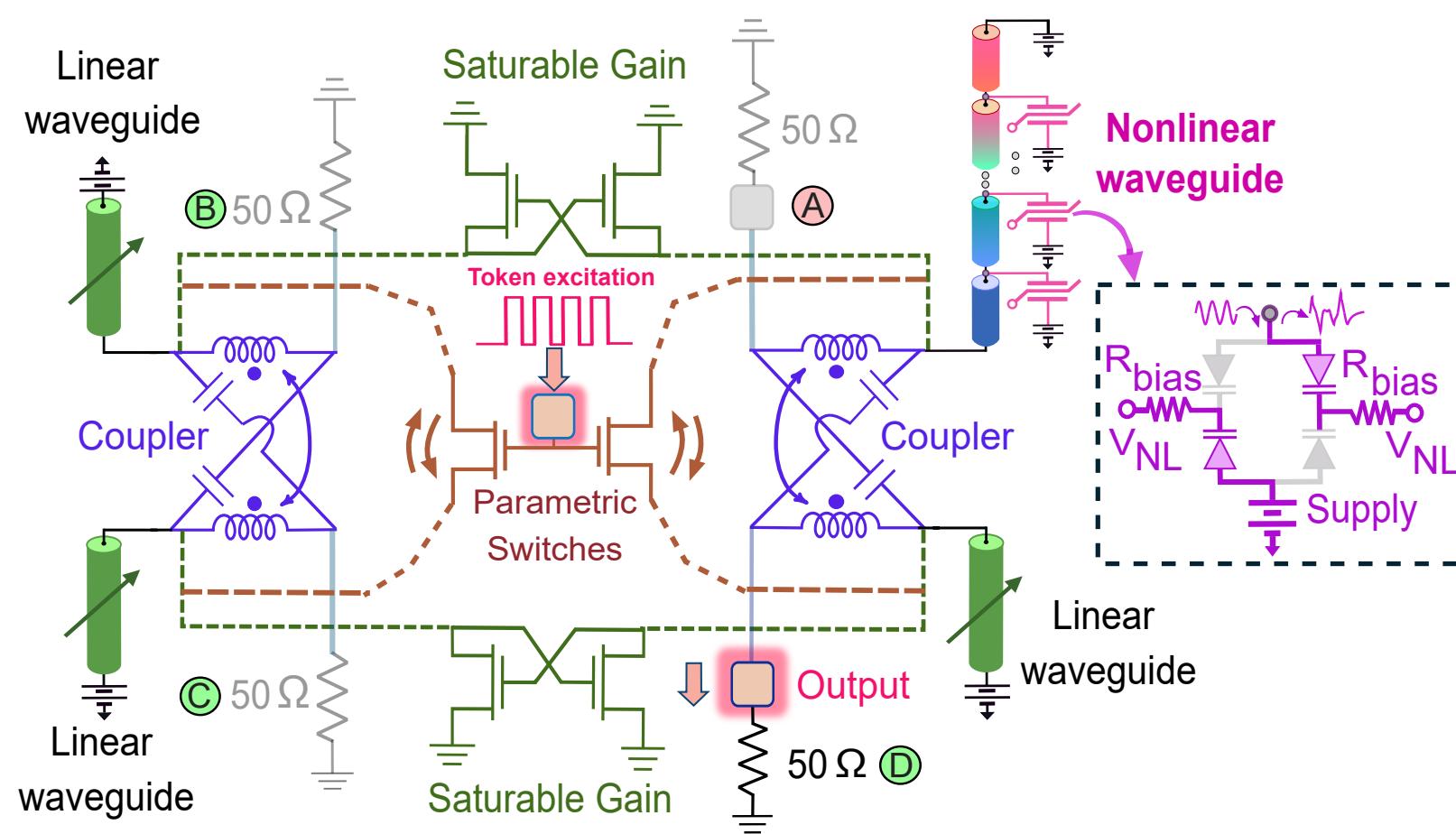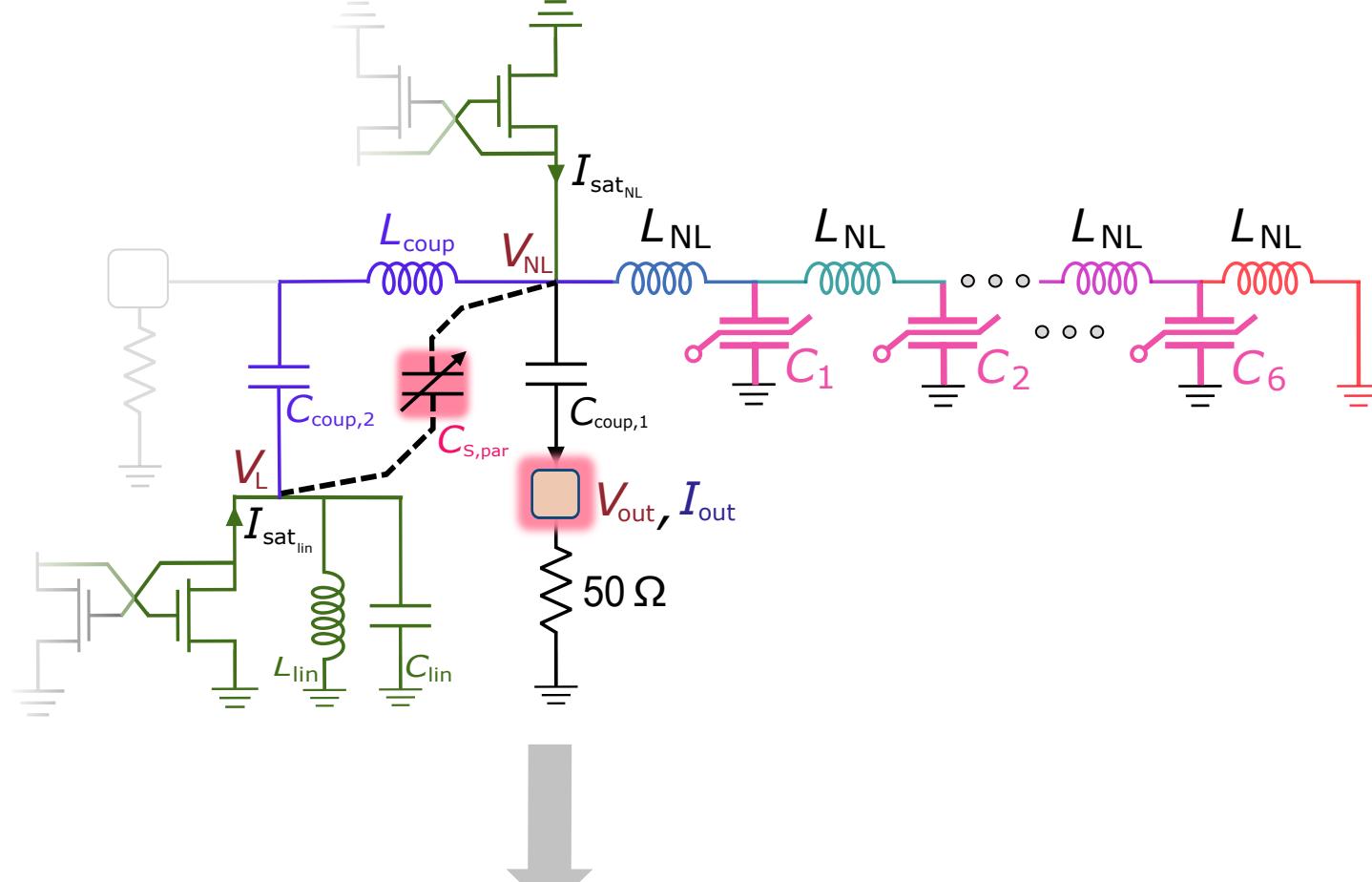
**b.** i. MNN configuration for broadband-input-driven oscillations
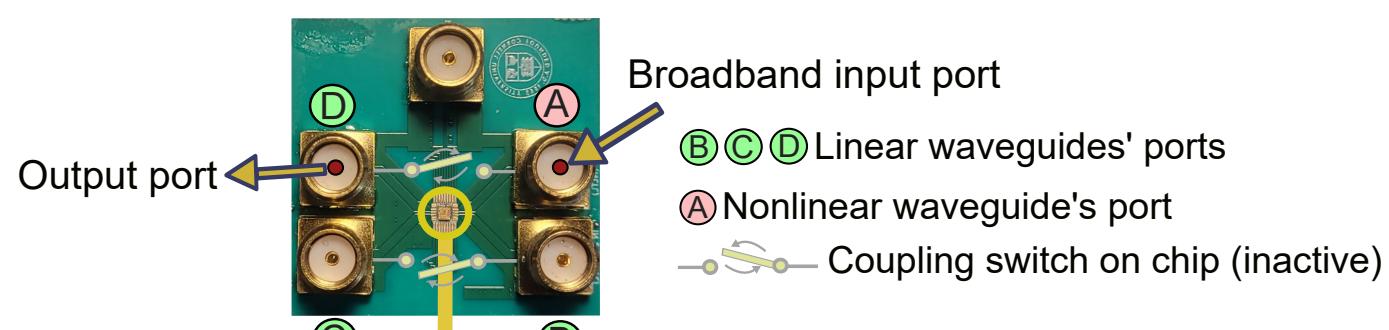
Broadband input port

Output port

Ⓑ Ⓒ Ⓓ Linear waveguides' ports
Ⓐ Nonlinear waveguide's port
Coupling switch on chip (inactive)

ii. Integrated circuit model for broadband-input-driven oscillations

Linear waveguide

Saturable Gain

Ⓑ 50 Ω

50 Ω Ⓐ

Broadband input

Nonlinear waveguide

Coupler

Coupler

Linear waveguide

Ⓒ 50 Ω

Saturable Gain

Output

50 Ω Ⓓ

iii. Reduced circuit model for broadband-input-driven oscillations

$I_{sat_{NL}}$

V_{in}, I_{in} L_{coup} V_{NL} L_{NL} L_{NL} L_{NL} L_{NL}

50 Ω $C_{coup,2}$ $C_{S,par}$ $C_{coup,1}$ C_1 C_2 C_6

V_L $I_{sat_{lin}}$ V_{out}, I_{out}

L_{lin} C_{lin} 50 Ω
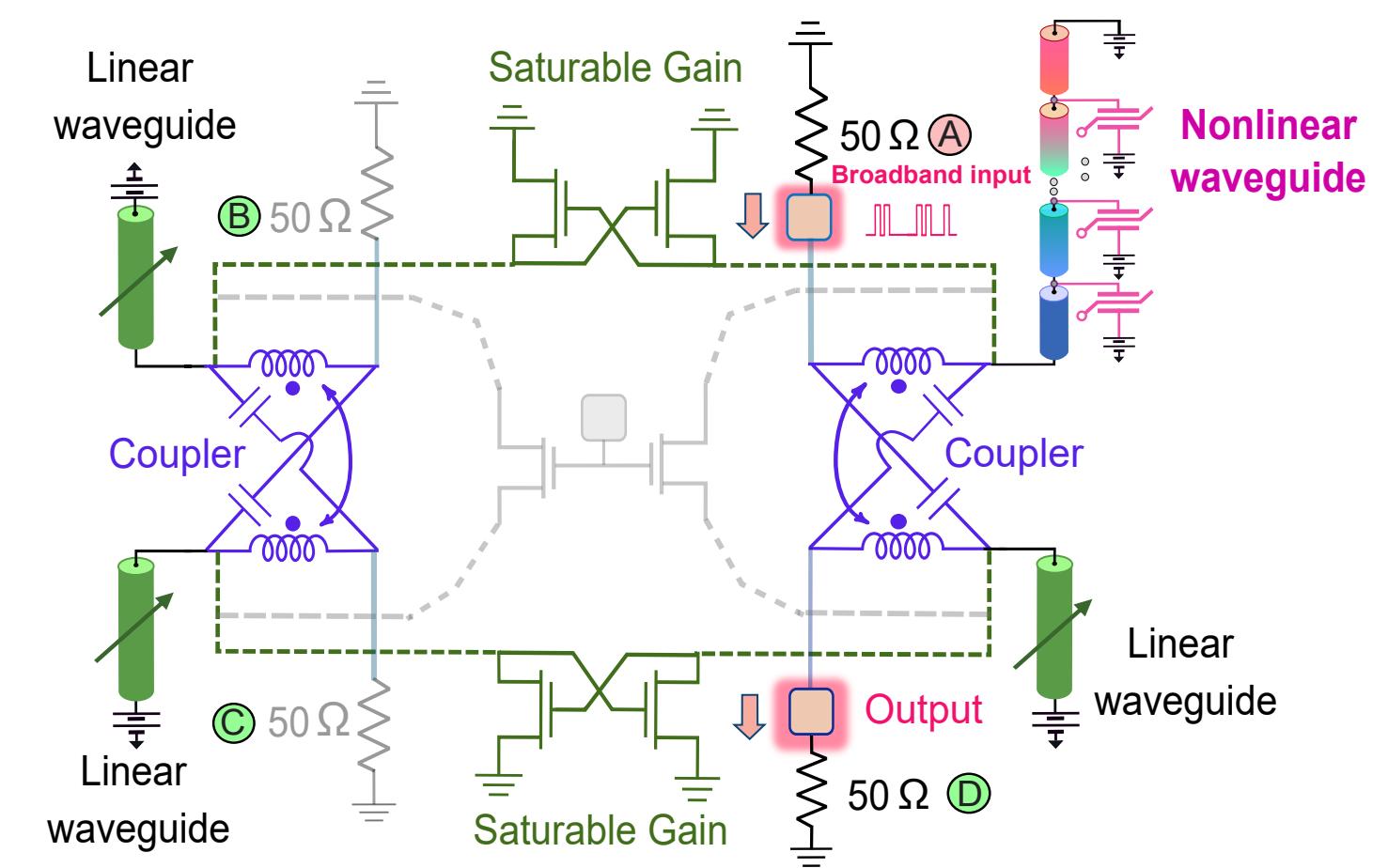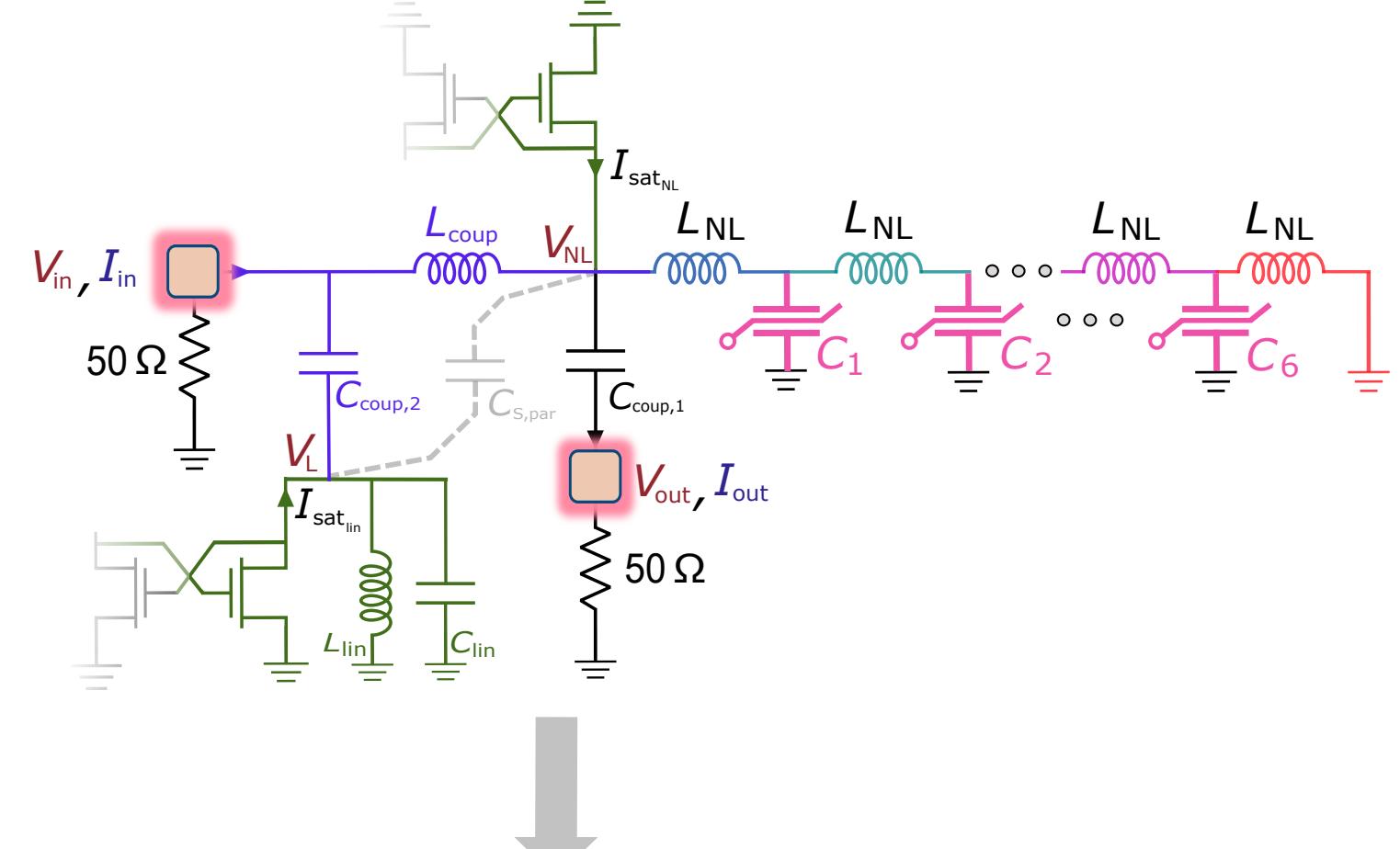
**c.**

i. Reduced coupled-mode model for token-encoded parametric oscillations

Saturable gain

C_{NL} C_{NL}

$\omega_{NL,1}$ $\omega_{NL,2}$ $\omega_{NL,3}$ $\omega_{NL,n}$

Data tokens
Token 1 Token 2
β_1,F_1,T_1 β_2,F_2,T_2

C_{pass}

$\gamma_{NL,1}^{int}$ $\gamma_{NL,2}^{int}$ $\gamma_{NL,3}^{int}$ $\gamma_{NL,n}^{int}$
(loss) (loss) (loss) (loss)

0 GHz 20 GHz

Output

ω_{Lin}

0 GHz 20 GHz

γ_{Lin}^{int}
(loss)

NL: Nonlinear mode
Lin: Linear mode
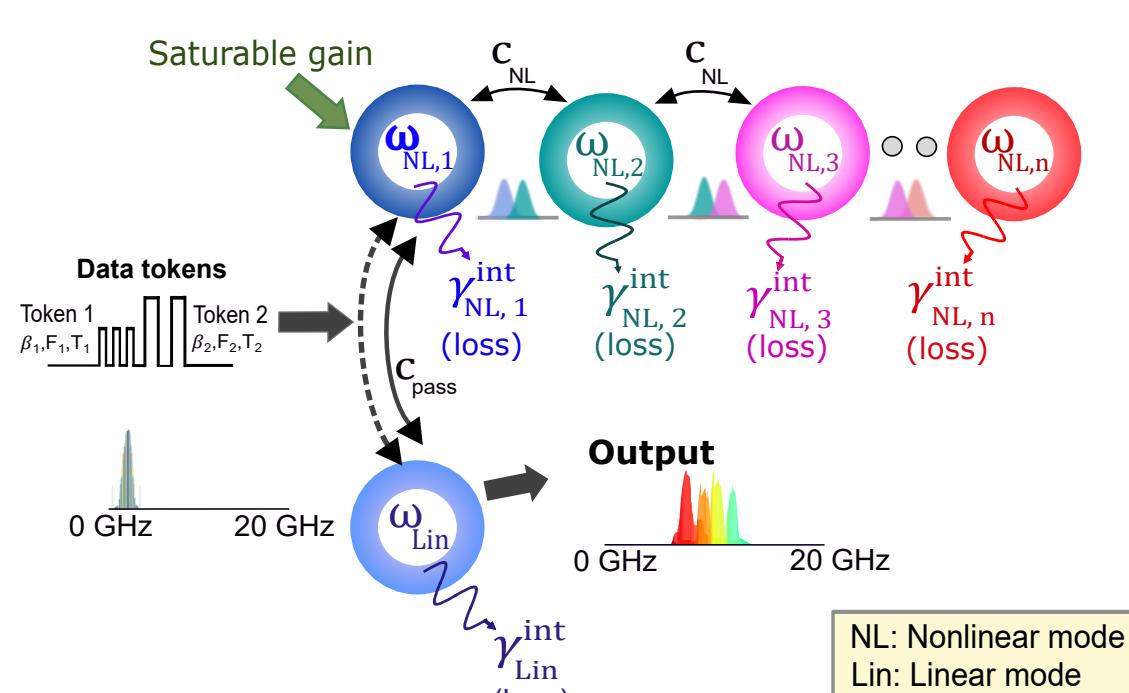
ii. Reduced coupled-mode model for broadband-input-driven oscillations

Saturable gain

C_{NL} C_{NL}

$\omega_{NL,1}$ $\omega_{NL,2}$ $\omega_{NL,3}$ $\omega_{NL,n}$

Fast data bits (*B*)

0 GHz 20 GHz

C_{pass}

$\gamma_{NL,1}^{int}$ $\gamma_{NL,2}^{int}$ $\gamma_{NL,3}^{int}$ $\gamma_{NL,n}^{int}$
(loss) (loss) (loss) (loss)

Output

ω_{Lin}

0 GHz 20 GHz

γ_{Lin}^{int}
(loss)

NL: Nonlinear mode
Lin: Linear mode
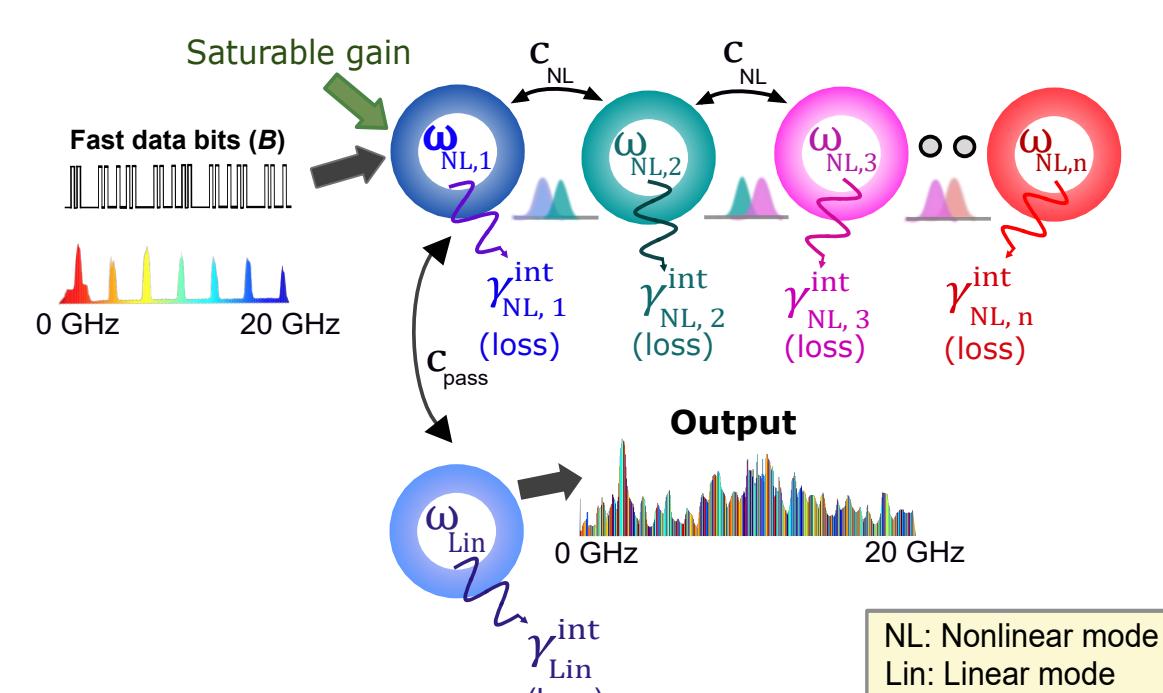
d. Coupled-mode simulations of steady-state spectra of token-encoded oscillations

i.

Amplitude modulation
$|\beta_{Tok}|$
$T_{Tok}= 4800/\omega_{NL}^o$
$F_{Tok}= 3\omega_{NL}^o/100$

$\beta_{Tok}= 0$
$\beta_{Tok}= 3$
$\beta_{Tok}= 6$

ii.

Duration modulation
T_{Tok}
$\beta_{Tok}= 4$
$F_{Tok}= 3\omega_{NL}^o/100$

$T_{Tok}= 1200/\omega_{NL}^o$
$T_{Tok}= 2400/\omega_{NL}^o$
$T_{Tok}= 4800/\omega_{NL}^o$

iii.

Frequency modulation
F_{Tok}
$\beta_{Tok}= 4$
$T_{Tok}= 4000/\omega_{NL}$

$F_{Tok}= \omega_{NL}^o/100$
$F_{Tok}= 3\omega_{NL}^o/100$
$F_{Tok}= 4\omega_{NL}^o/100$
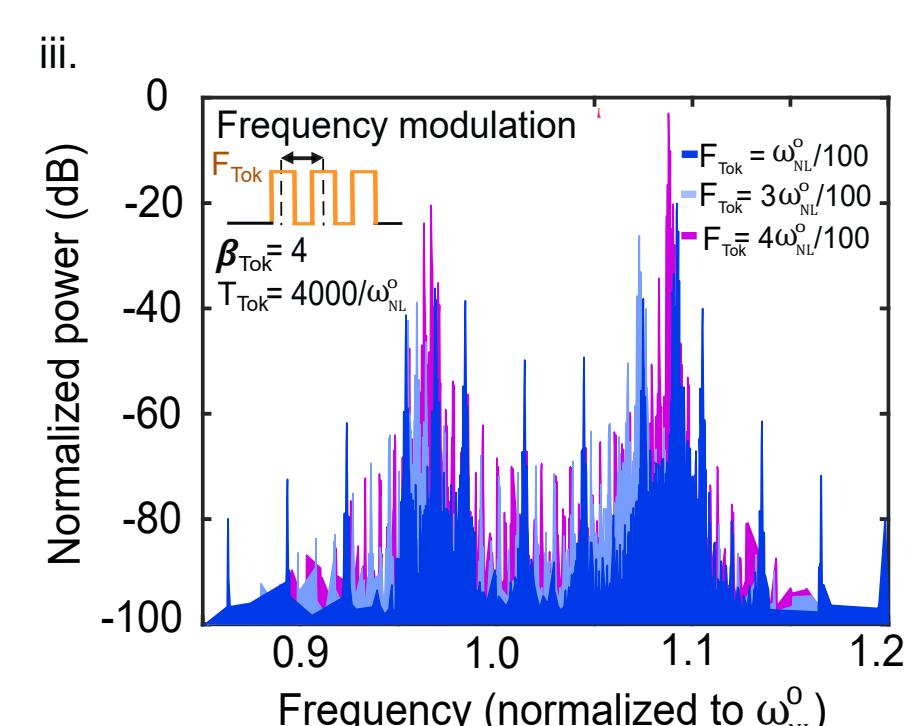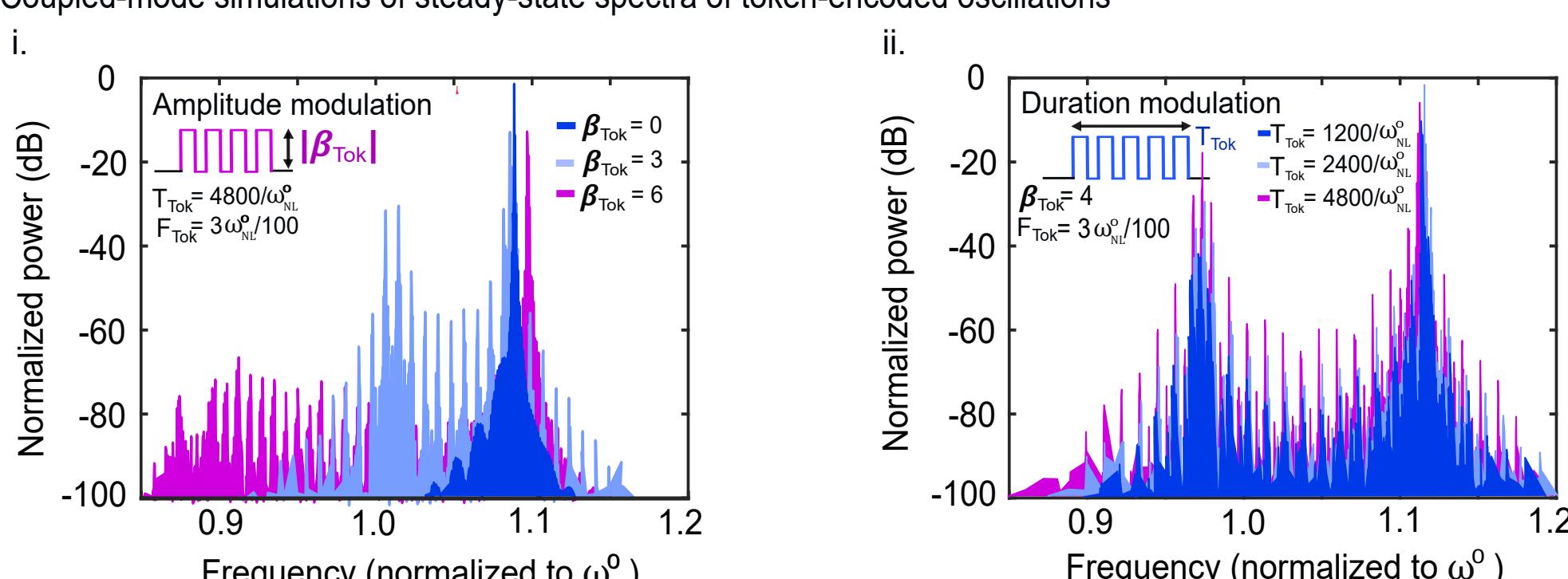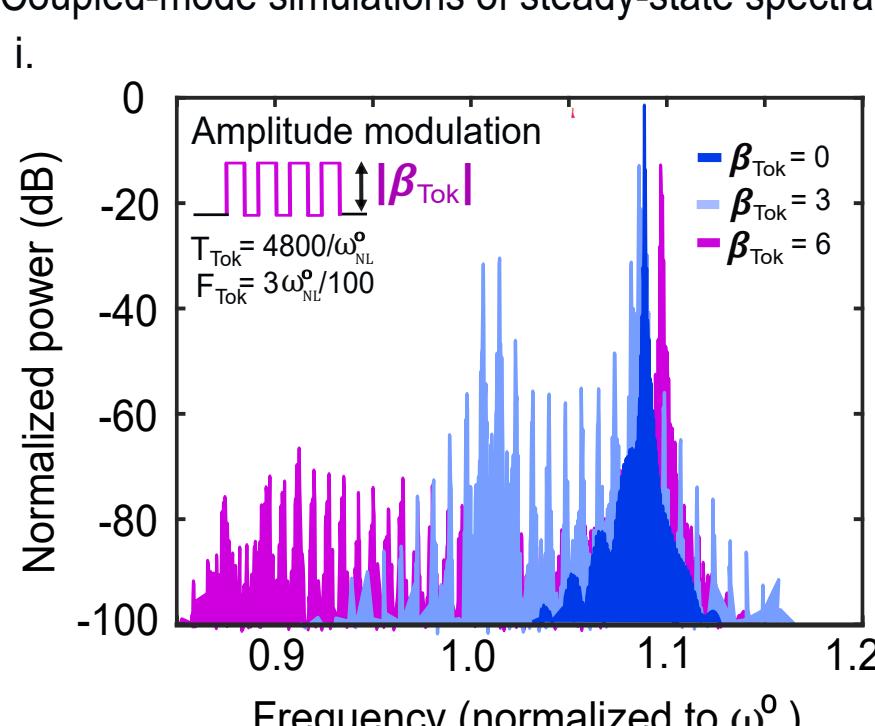
Extended Data Figure. 1 – Integrated circuit and coupled-mode model for feature extraction with the MNN. a, The MNN is mounted on a compact PCB and accessed through five RF ports: four for the waveguides and one for the parametric analog data token input (**a.i** and **b.i**). Each linear waveguide (B,C and D) is implemented as a coiled transmission line stub with inductive sub-segments L_{lin} which are selectively grounded via switches that truncate propagation length. On chip (**a.ii** and **b.ii**), the nonlinear waveguide (A) is a transmission line loaded with polynomially nonlinear capacitors to form C–L–C Π nonlinear resonator sections coupled by delays. Input power is distributed through a pair of symmetric Lange couplers. The left coupler feeds two linear waveguides, and the right coupler feeds one linear and one nonlinear path. Cross-coupled transistor pairs provide saturable gain to compensate internal loss. The parametric switches are used when analog data tokens modulate the comb spectrum for feature expansion (**a.ii**) and are left inactive when high-speed broadband data directly drives the waveguides (**b.ii**) for reduced-bandwidth feature extraction. For analysis (**a.iii** and **b.iii**), the linear resonators can be simplified to single-mode tank circuits. The left half of the network can be ignored because the linear resonators are far-detuned (around 50 GHz) from the nonlinear waveguide's modes' primary range (below 15 GHz), resulting in weak interaction. The primary coupling occurs between the nonlinear waveguide and the linear resonator on the right through a parametric switch modeled as time-varying capacitor, and a fixed delay path through the coupler. The tunable capacitance transitions between effectively open- and short-circuit states, with coupling strength controlled by token amplitude (β_{Tok}), pulse frequency (F_{Tok}) and pulse-train duration (T_{Tok}). **c,** The resulting reduced coupled-mode model consists of a cascade of nonlinear resonators connected to a linear resonator via parametric switching (not active for purely fast-bitstream-driven waveguides) and fixed-delay coupling. Here, saturable gain offsets internal losses. These modes hybridize on interaction with the incoming gigabit-per-second data or analog data tokens. **d,** Simulations of steady-spectra reproduce experimentally seen trends in reshaping the MNN's comb (Fig. 2b) when tokens' parameters are varied, especially token amplitude (**d.i**).