A Small, Low Power Boost Regulator Optimized for Energy Harvesting Applications

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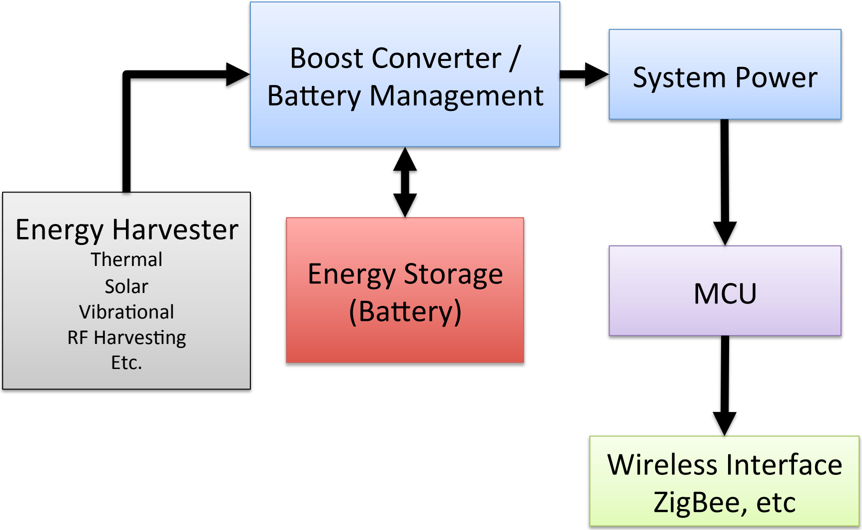
Outline

Current Energy Harvesting Systems



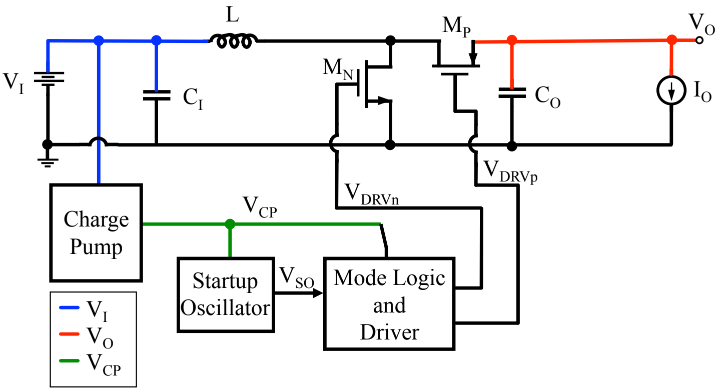
- Battery/energy storage device must be replaced regularly

Design Specifications

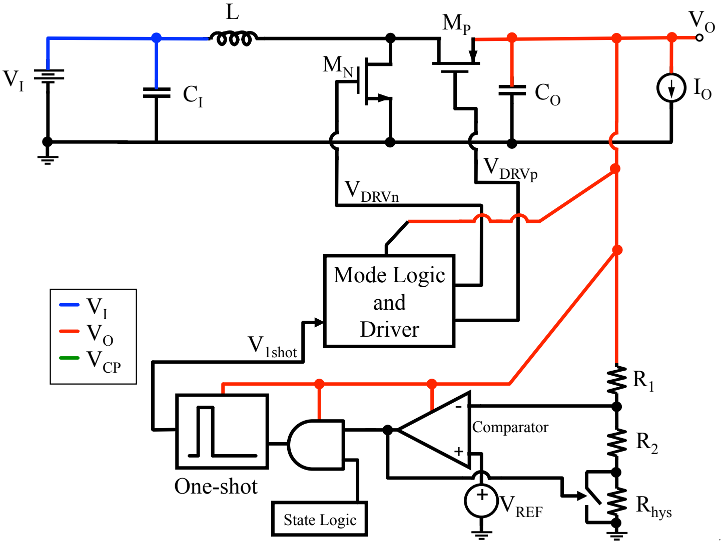
1. Startup from input voltage below $V_{t(NMOS)}$
   - Works down to $V_{IN} = 240$mV
2. Efficiency $> 95\%$
   - Low I_Q ($\approx 15\mu$A)
   - Low conduction losses
   - Low switching losses
3. Output Load $>$ 5mW

Target application: low-power microcontroller and wireless interface

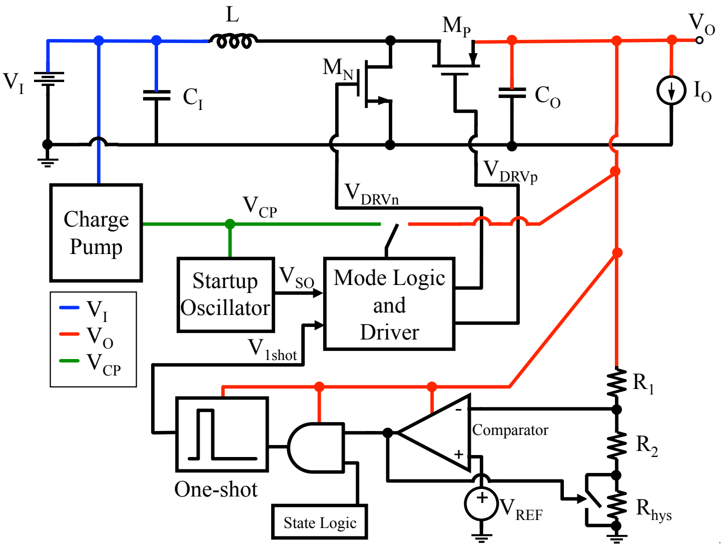
Initial Startup Block Diagram



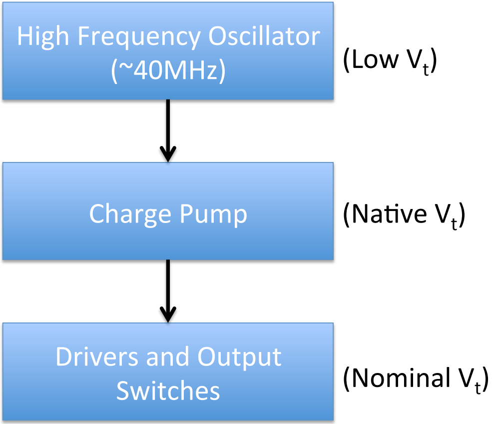
Steady-State Block Diagram



Overall System Block Diagram

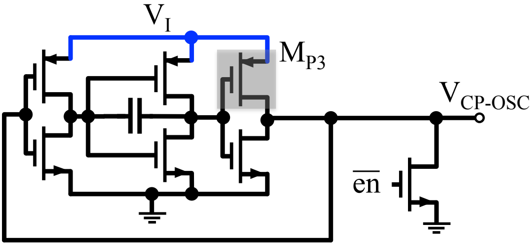


Startup Flowchart



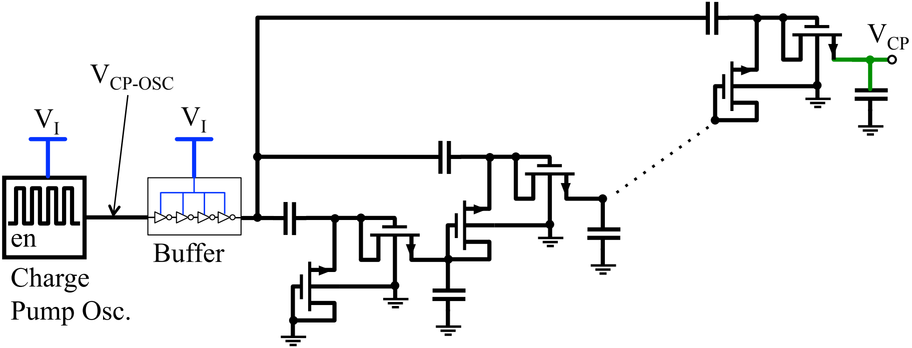
Transistor Type	*Model* V_{t0}
Native NMOS	-0.02V
Low–V_t PMOS	-0.13V
Low–V_t NMOS	0.27V
Nominal–V_t PMOS	-0.44V
Nominal–V_t NMOS	0.44V

Charge Pump Oscillator



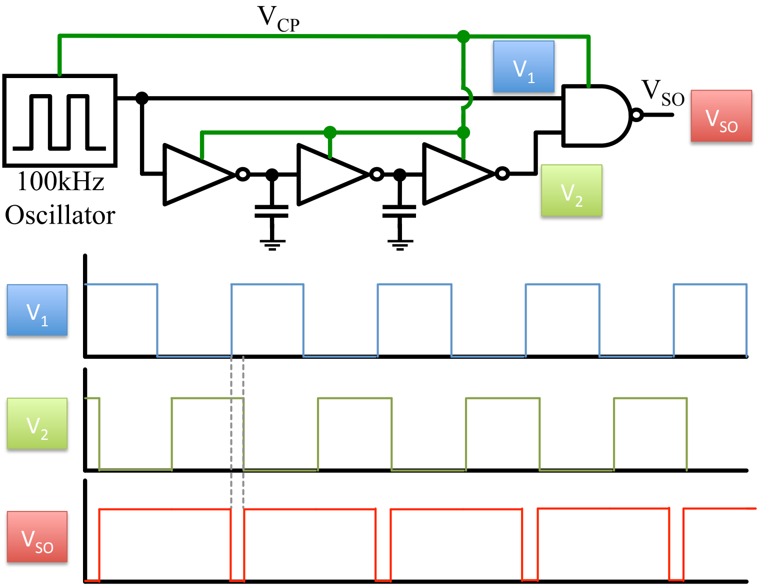
1. Transistor M_{P3} has long length $(W/L = 2\mu/5\mu)$
   - Other PMOS have $W/L = 2\mu m/0.25\mu m$
   - Shutdown leakage current is very small (≈1μA)
2. Capacitor (20fF) sets oscillation frequency
   - Oscillator operates at ≈ 40MHz

Full Charge Pump Schematic

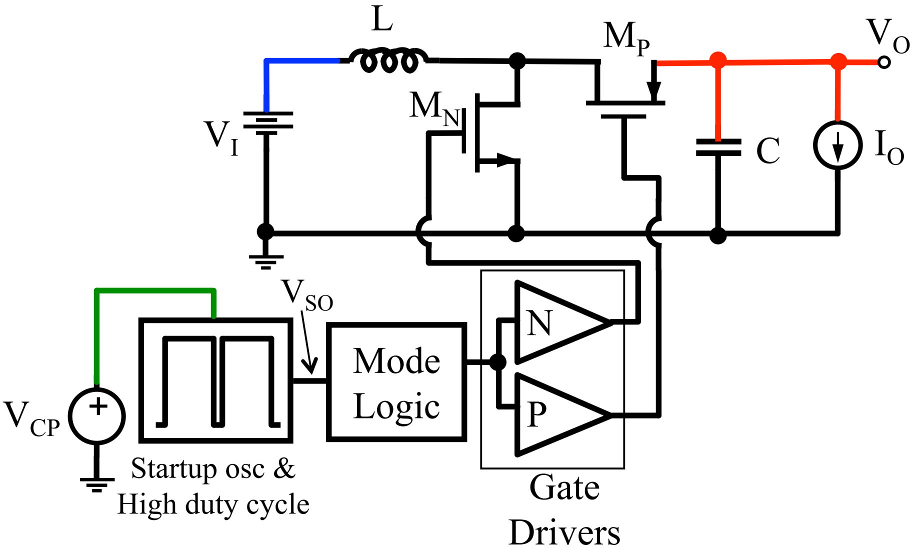


1. All NMOS are native devices
   - $V_{t0} \approx 0\text{V}$
2. All capacitors are 10pF
3. Currently using 10 gain stages

High Duty-Cycle Startup Circuit



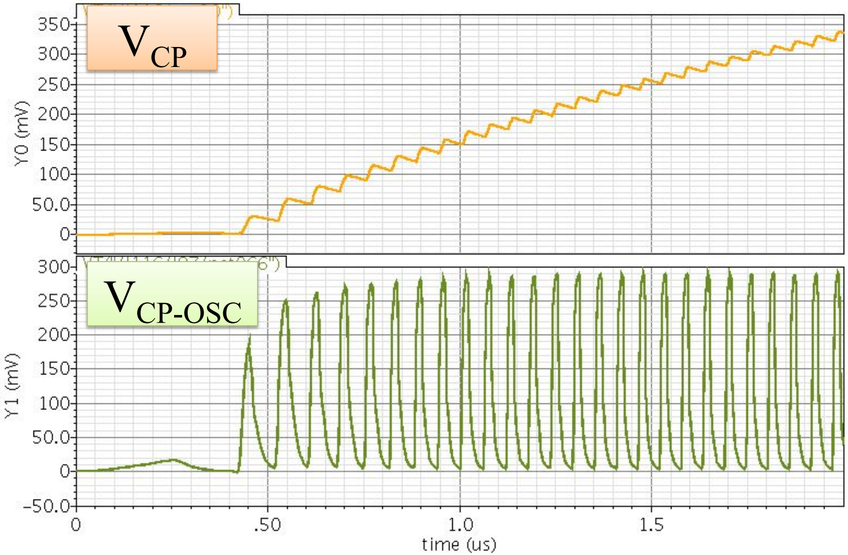
Full Startup Schematic



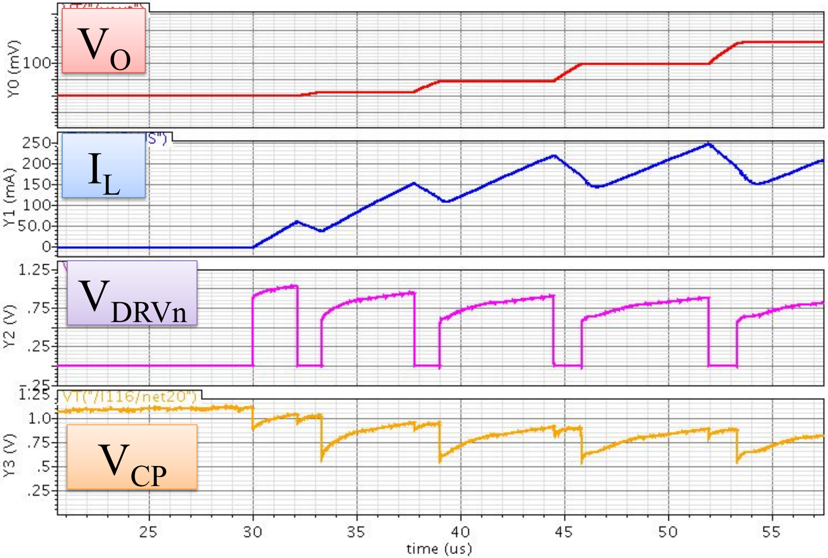
Simulation Parameters

Circuit Component	Value
V_I	300mV
V_O	1.0V
L	10μH
C_I	2.2μF
C_O	5.0μF
t_{on}	1.5μs
V_{REF}	500mV
NMOS	5mm / 0.18μm
PMOS	10mm / 0.18μm

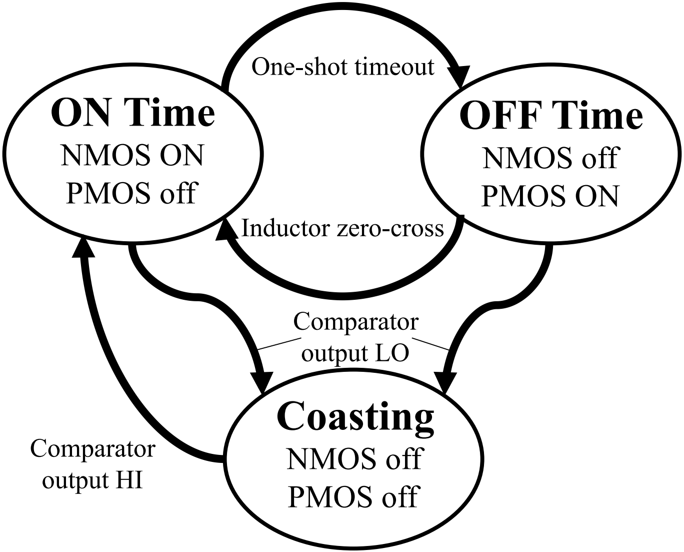
Charge Pump Startup Simulation



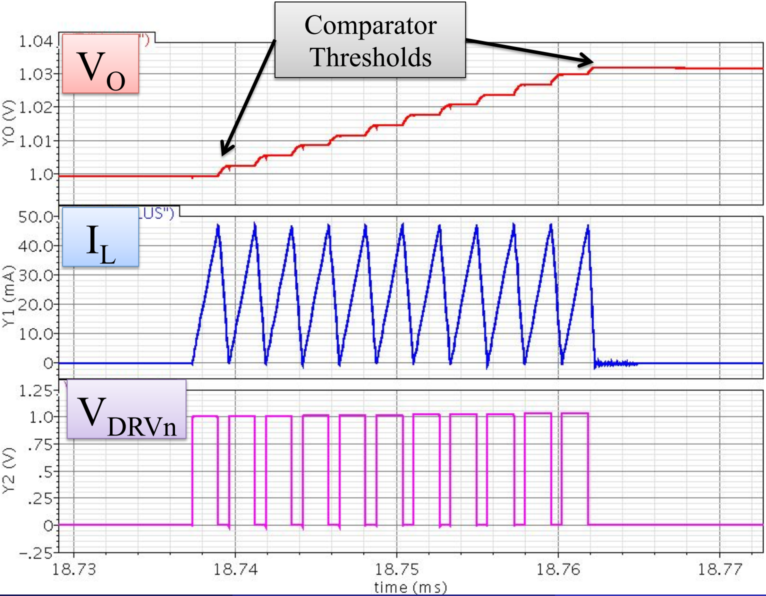
Full Startup Simulation



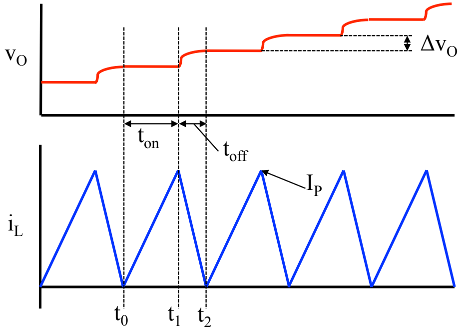
State Diagram: Steady State Operation



Steady State Operation Simulation



Calculations



- Inductor current equation

$$i_L(t) = \begin{cases} \dfrac{V_I}{L}t, & t_0 < t \le t_1 \\ I_P - \dfrac{V_O - V_I}{L}(t - t_1), & t_1 < t \le t_2 \end{cases}$$

Calculations Continued

- Output voltage ripple

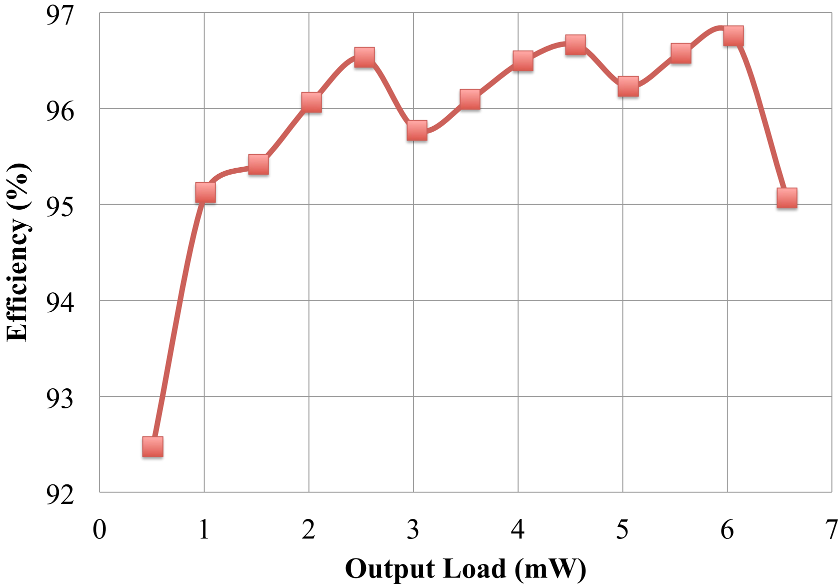
$$\Delta v_O = \frac{1}{C_O}\int i_L(t)\,\mathrm{d}t = \frac{I_P^2 L}{2C_O(V_O - V_I)}$$

$$\Delta v_O = t_{on}^2 \frac{V_I^2}{2LC_O(V_O - V_I)}$$

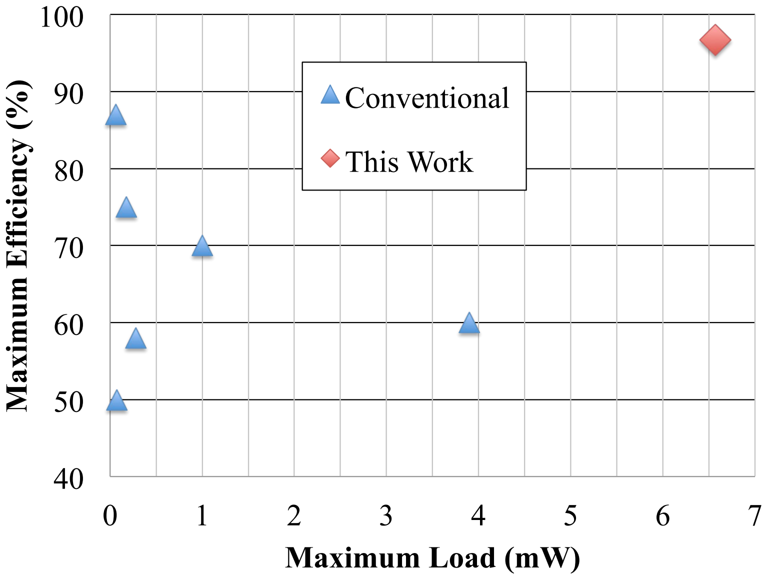
- Maximum load current

$$I_{O(max)} = t_{on}\frac{V_I^2}{2LV_O}$$

Circuit Efficiency



Efficiency Comparison



Conclusion

1. Introduced bootstrapped boost for EH applications
2. Better performance than previous works
   - Higher efficiency
   - Extended load range
3. Only requires 3 external components
   - Input capacitor, output capacitor, inductor
   - No external energy storage components
4. Future work
   - Create chip in actual Si
   - Continue to optimize key parameters
     - Minimum V_{IN}, efficiency, etc.

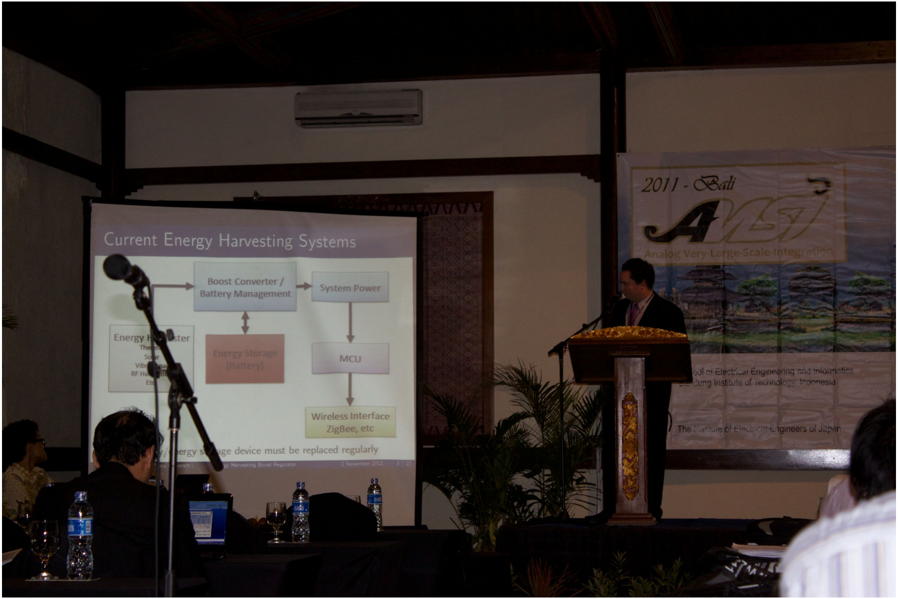
Fin

- Questions?

Questions From the Audience

1. Maximum power point is not always at the same voltage. Have you considered MPPT or similar?
   - This is not something I have considered yet
2. What limits the minimum input voltage?
   - Limited by the charge pump oscillator $(V_{IN(min)} = 240mV)$
3. You are using a lot of strange devices–what process are you using?
   - TSMC 0.18μm CMOS process that has Native–, Low– and Nominal–V_t devices
4. Have you looked into the output impedance of your circuit and how it affects efficiency?
   - This isn't something I have looked at yet
5. Are you using adaptive on time control?
   - At this time, the on time is just a constant value

Photos


Current Energy Harvesting Systems
Boost Converter / Battery Management
System Power
Energy Storage (Battery)
MCU
Wireless Interface ZigBee, etc
2011 - Bali
Analog Very-Large-Scale-Integration

Food




Strange Fruits




Banquet

Scenery 1

Scenery 2

Pool

Beach