Interferometer Photo Detector Circuit

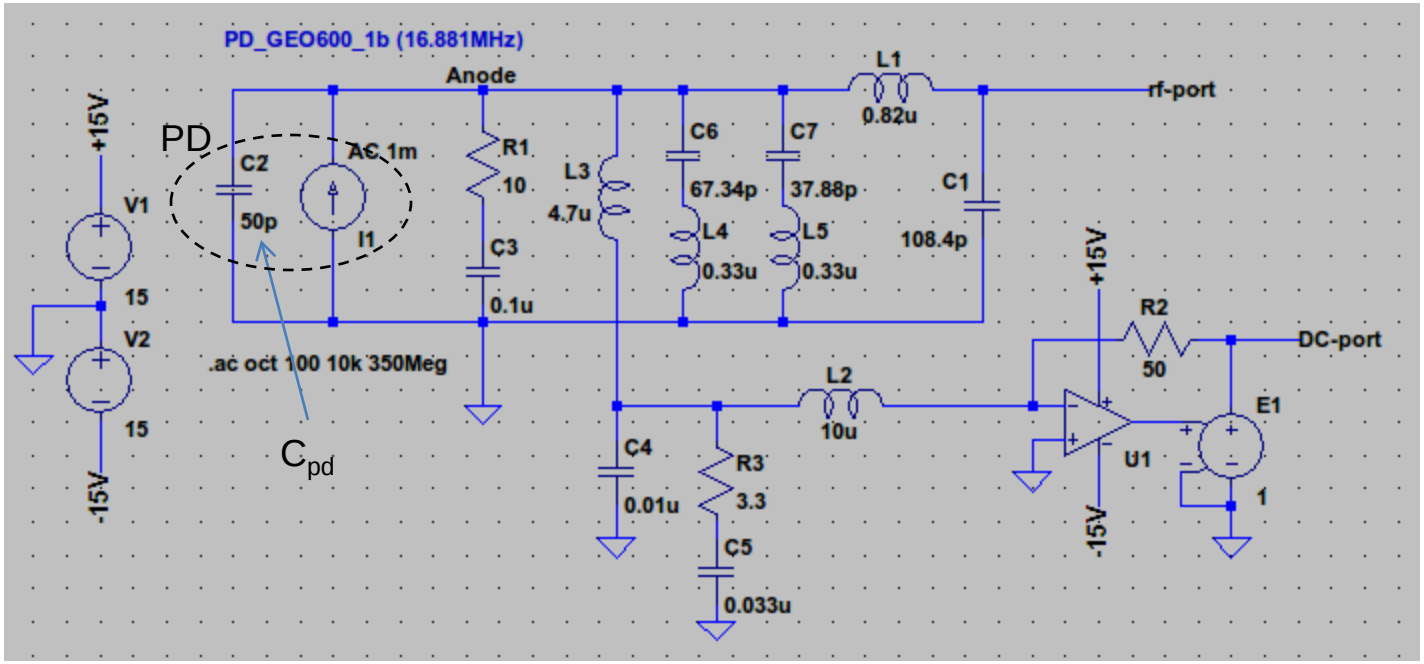
（2012/5/24 麻生氏提供の受光パワー・データ（再計算値）による）

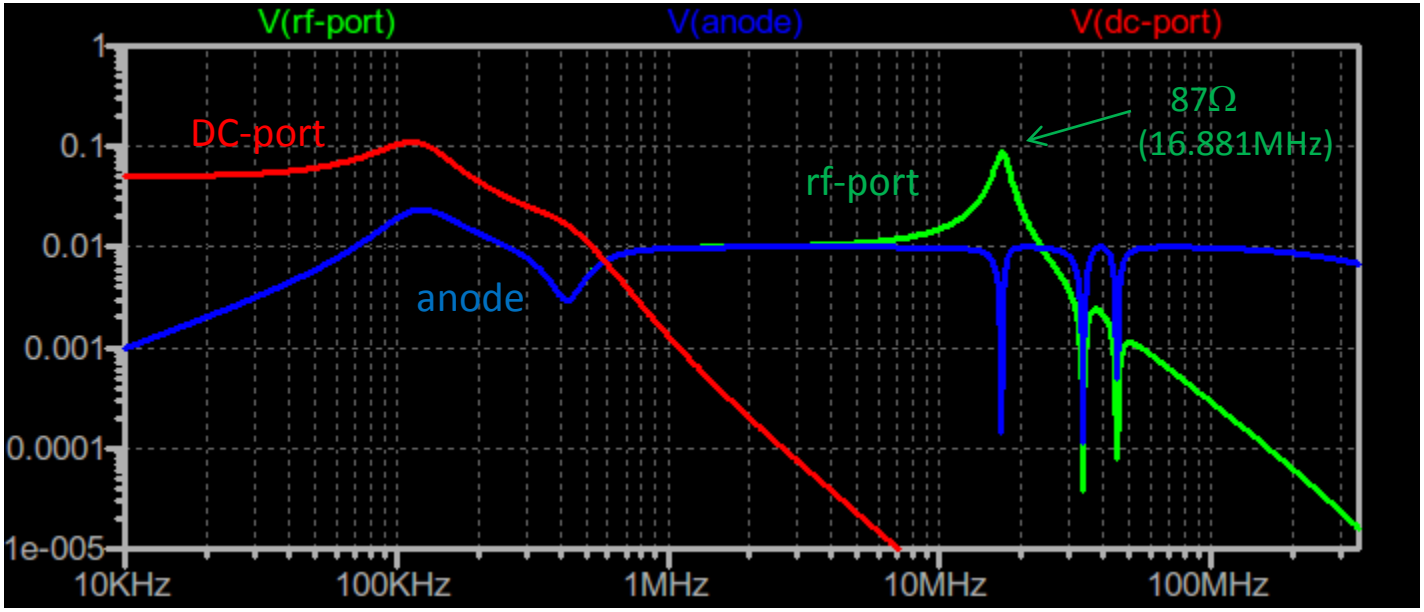
2012/5/31

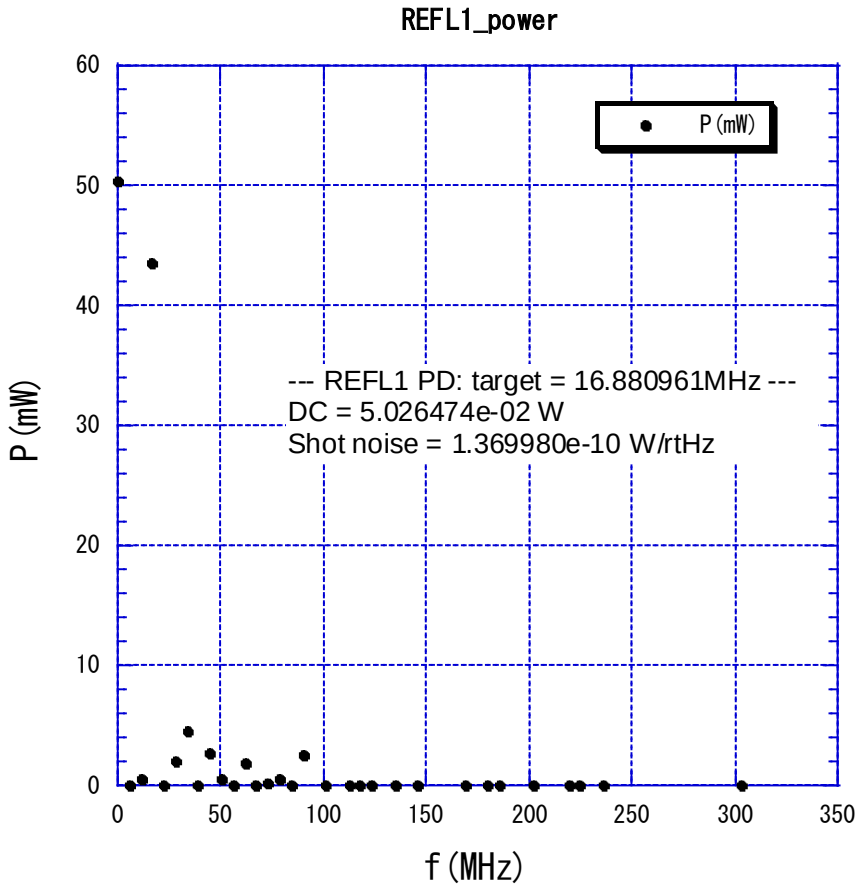
(2012/6/4 修正：OP amp ノイズ追加)

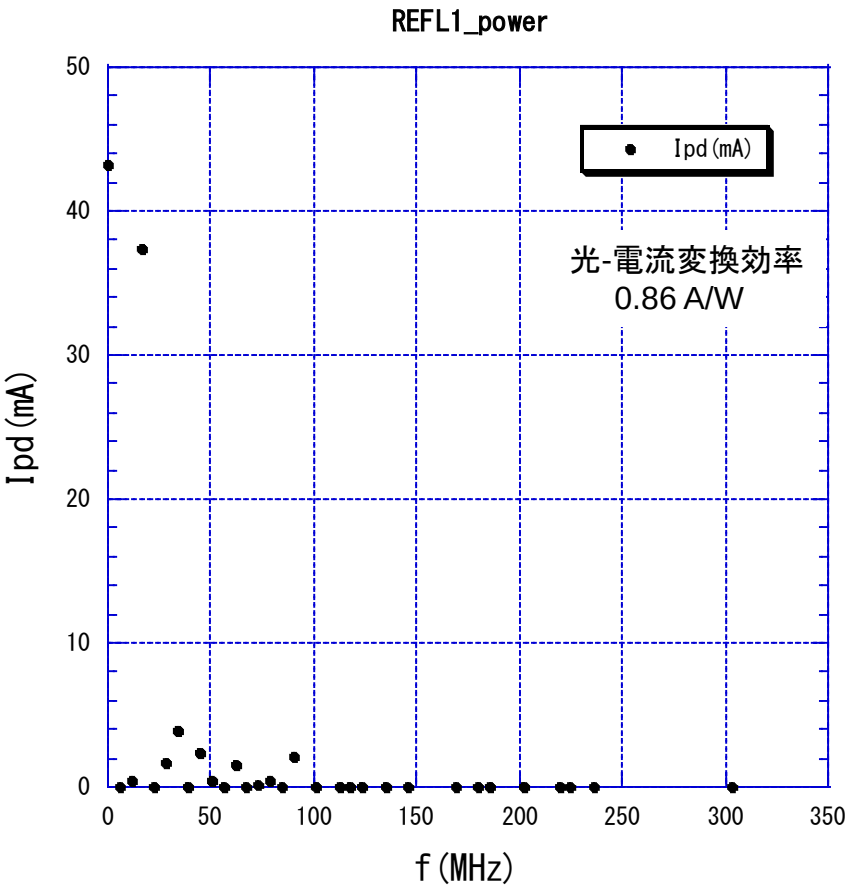
平松成範

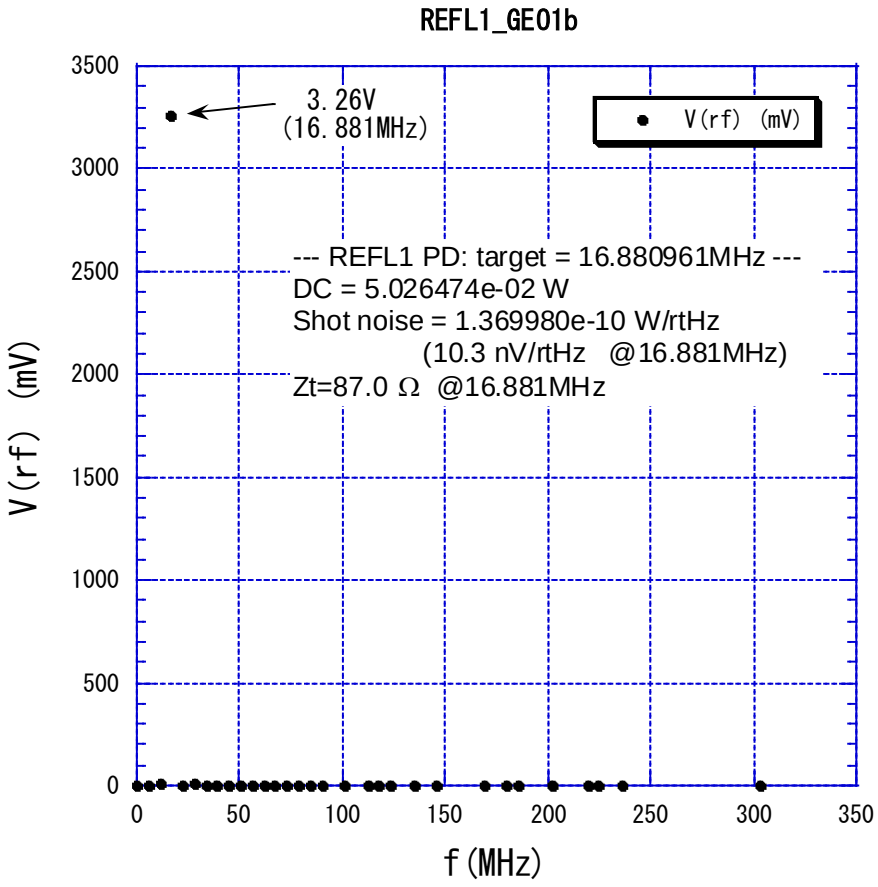
Circuit : GEO600_1b (f_0=16.811MHz : C_{pd}=50pF, L_1=0.82μH, C_1=108.4pF, R_1=10Ω)

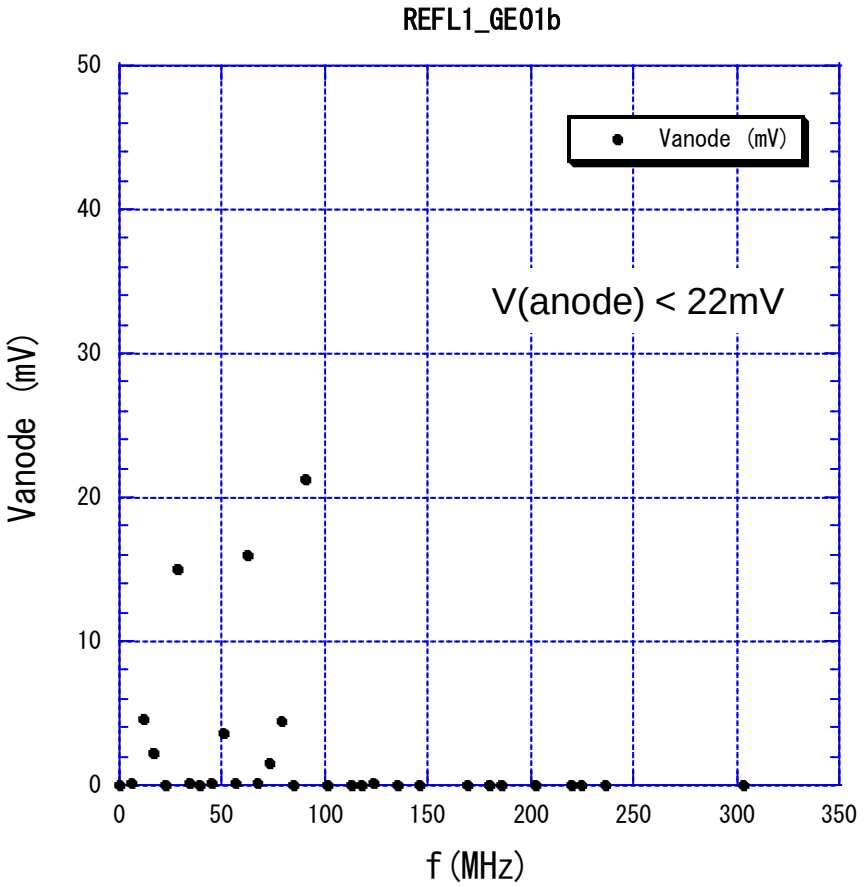


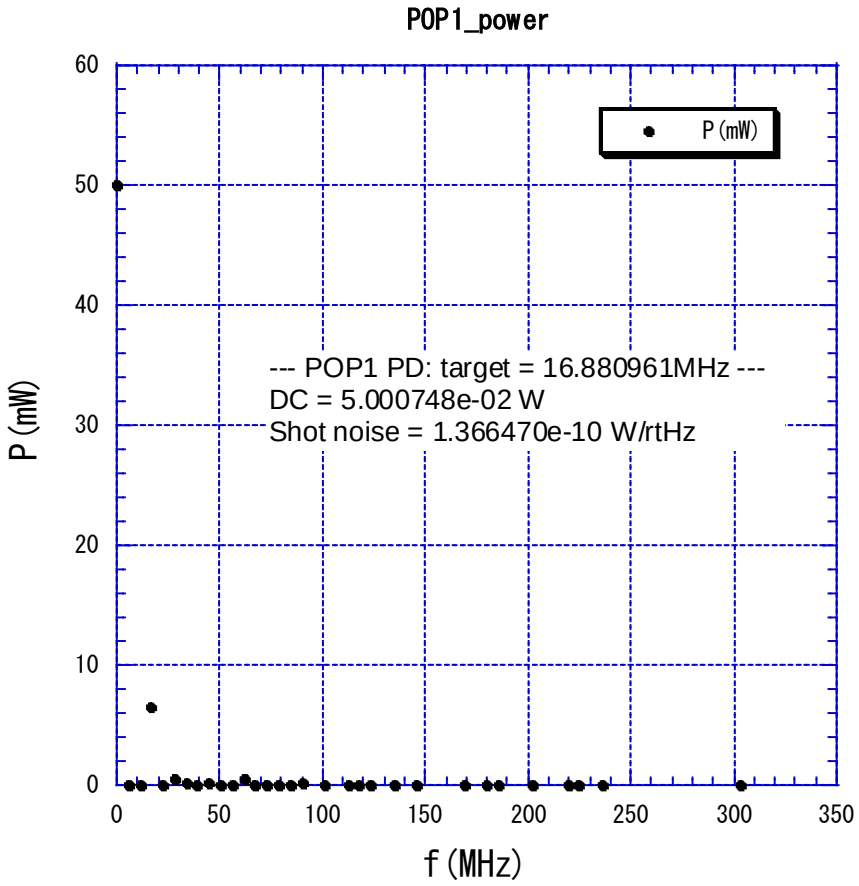


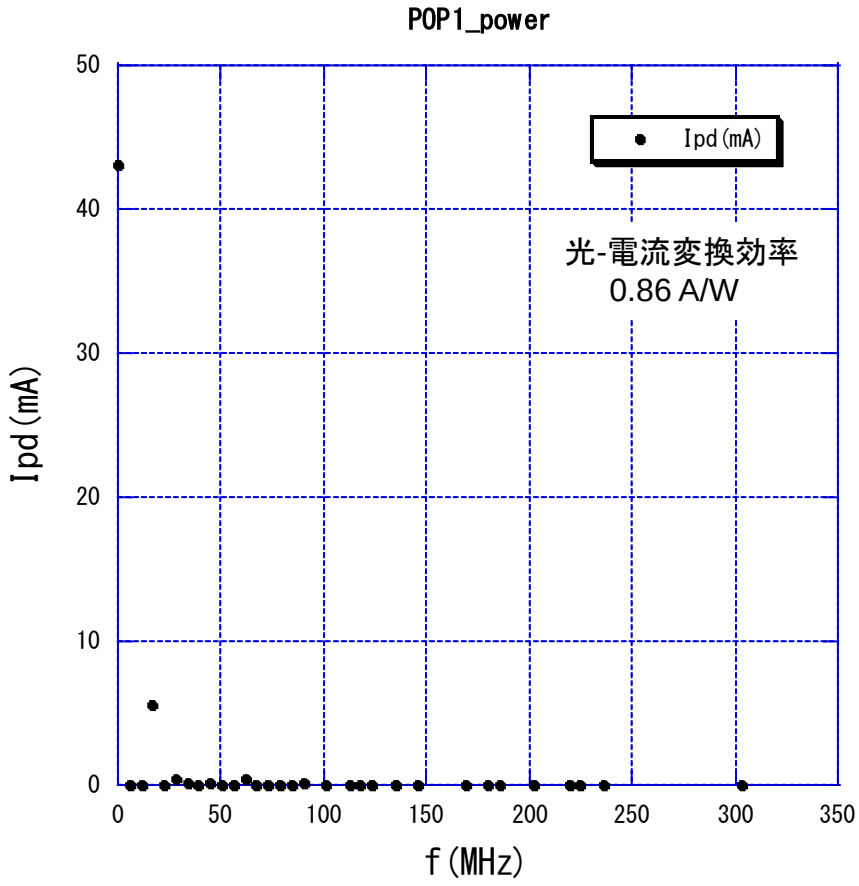

REFL1_power
P (mW)
--- REFL1 PD: target = 16.880961MHz ---
DC = 5.026474e-02 W
Shot noise = 1.369980e-10 W/rtHz
P (mW)
f (MHz)
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350

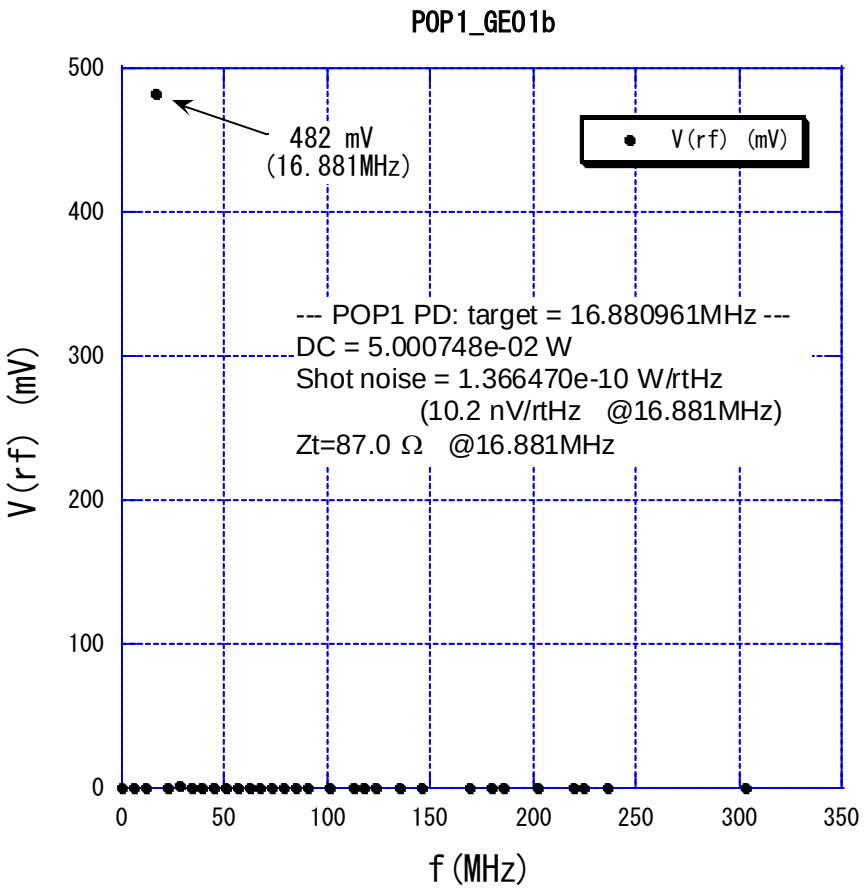

REFL1_power
Ipd (mA)
光-電流変換効率
0.86 A/W
Ipd (mA)
f (MHz)
0
10
20
30
40
50
0
50
100
150
200
250
300
350

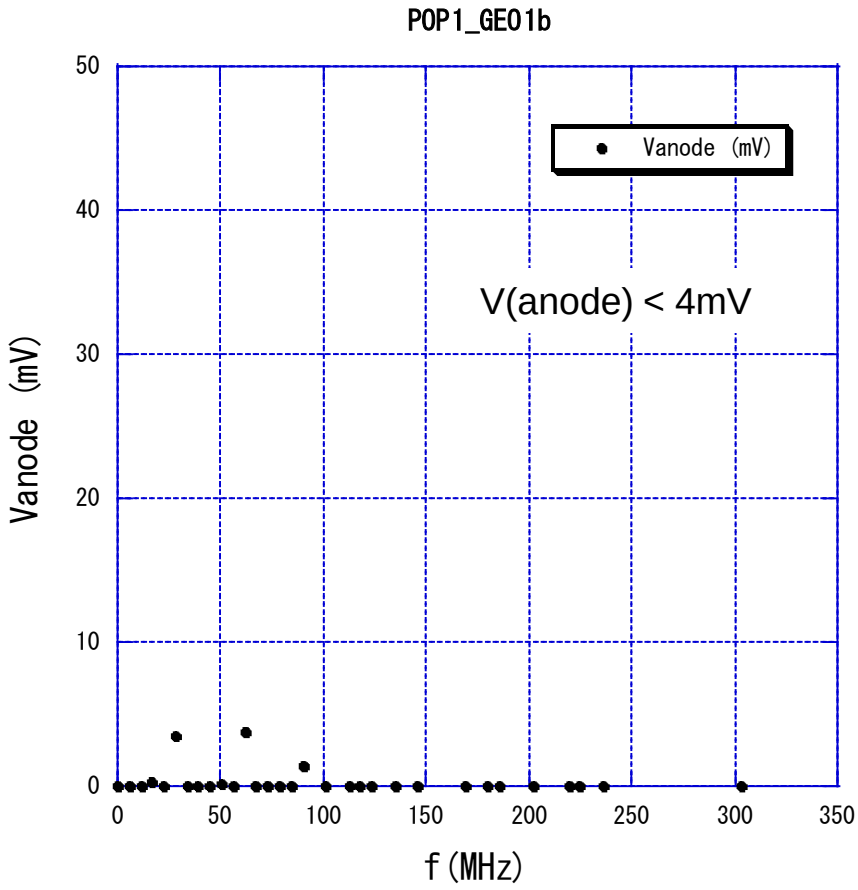

REFL1_GE01b
3.26V
(16.881MHz)
V(rf) (mV)
--- REFL1 PD: target = 16.880961MHz ---
DC = 5.026474e-02 W
Shot noise = 1.369980e-10 W/rtHz
(10.3 nV/rtHz @16.881MHz)
Zt=87.0 Ω @16.881MHz
V(rf) (mV)
f (MHz)
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
300
350

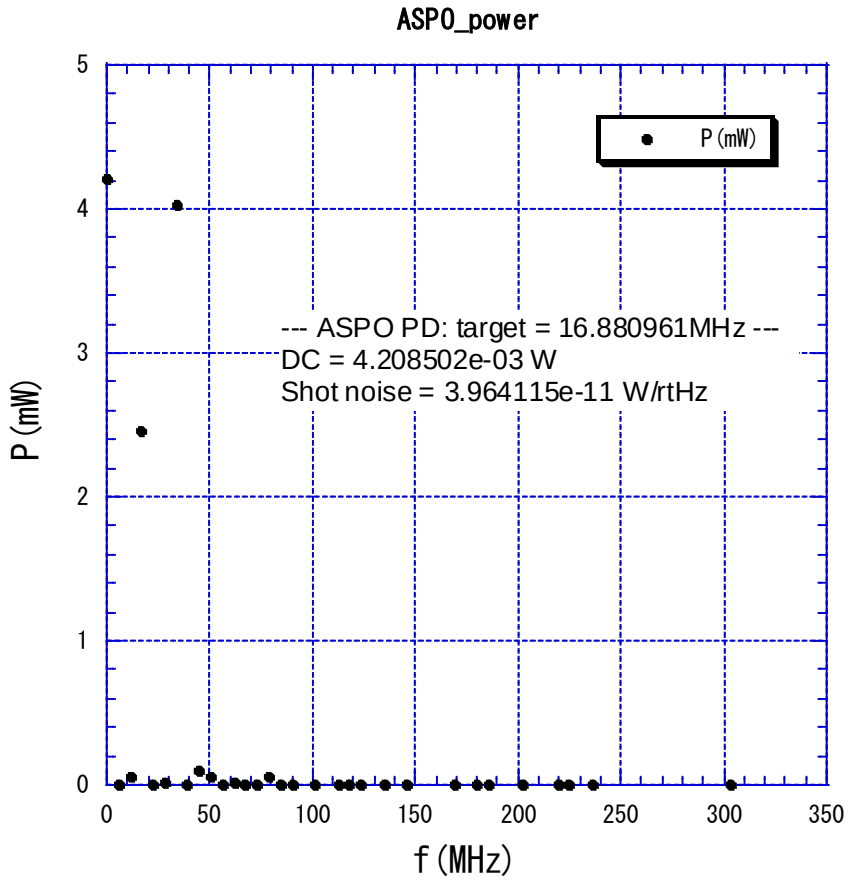

REFL1_GE01b
Vanode (mV)
V(anode) < 22mV
Vanode (mV)
f (MHz)
0
10
20
30
40
50
0
50
100
150
200
250
300
350

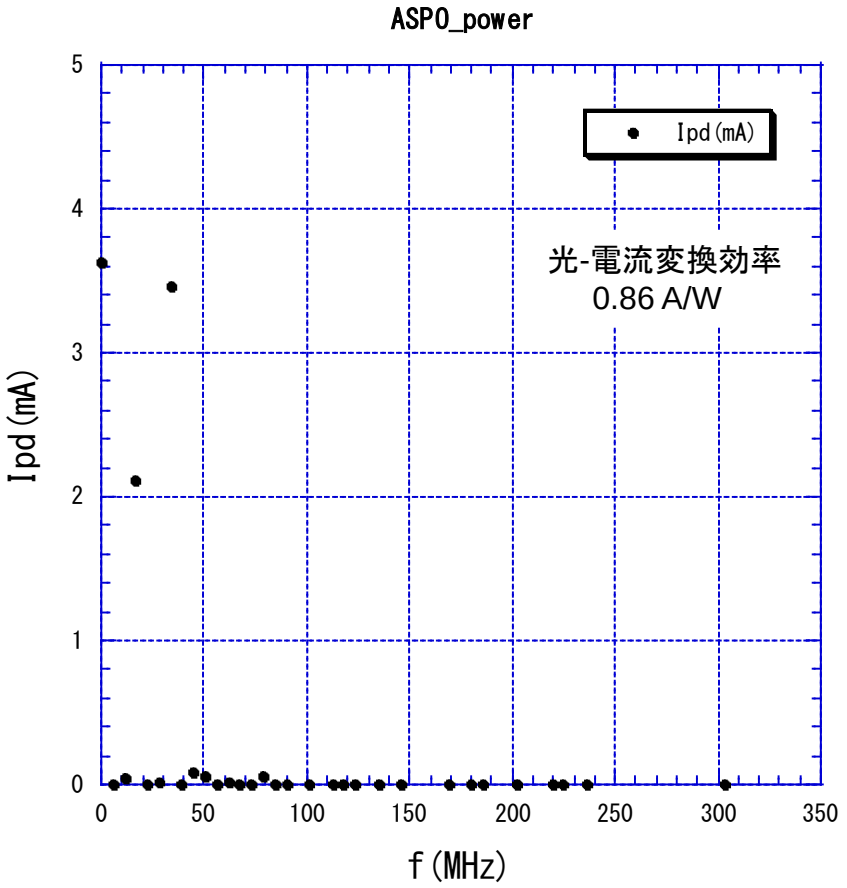

POP1_power
P (mW)
--- POP1 PD: target = 16.880961MHz ---
DC = 5.000748e-02 W
Shot noise = 1.366470e-10 W/rtHz
P (mW)
f (MHz)
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350

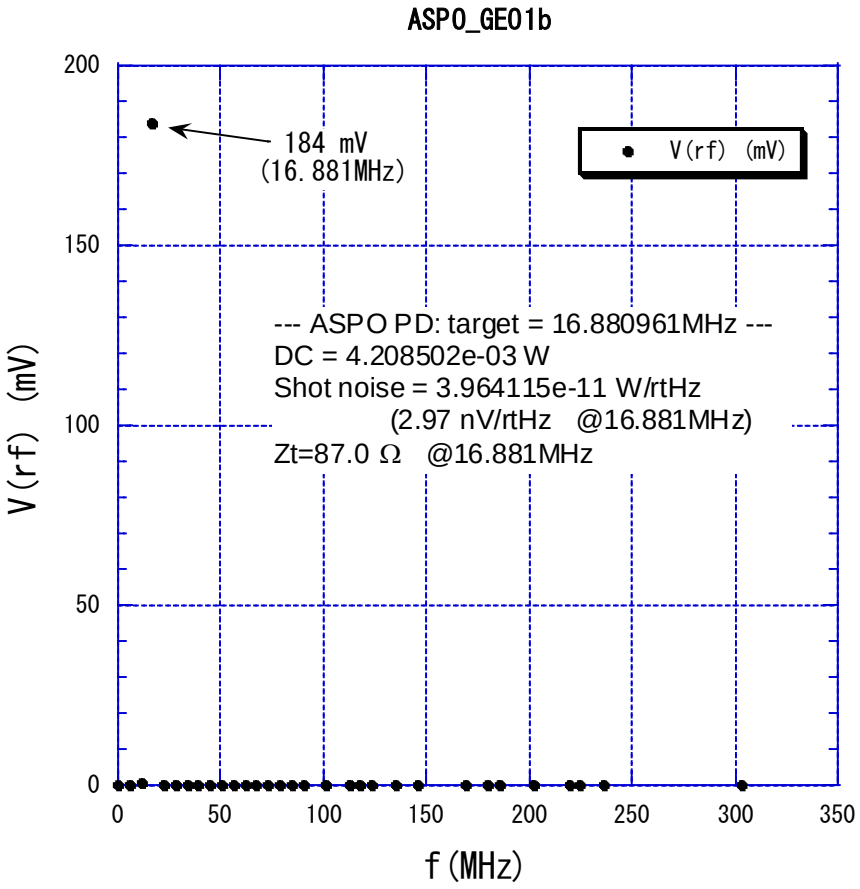

POP1_power
Ipd (mA)
光-電流変換効率
0.86 A/W
Ipd (mA)
f (MHz)
0
10
20
30
40
50
0
50
100
150
200
250
300
350

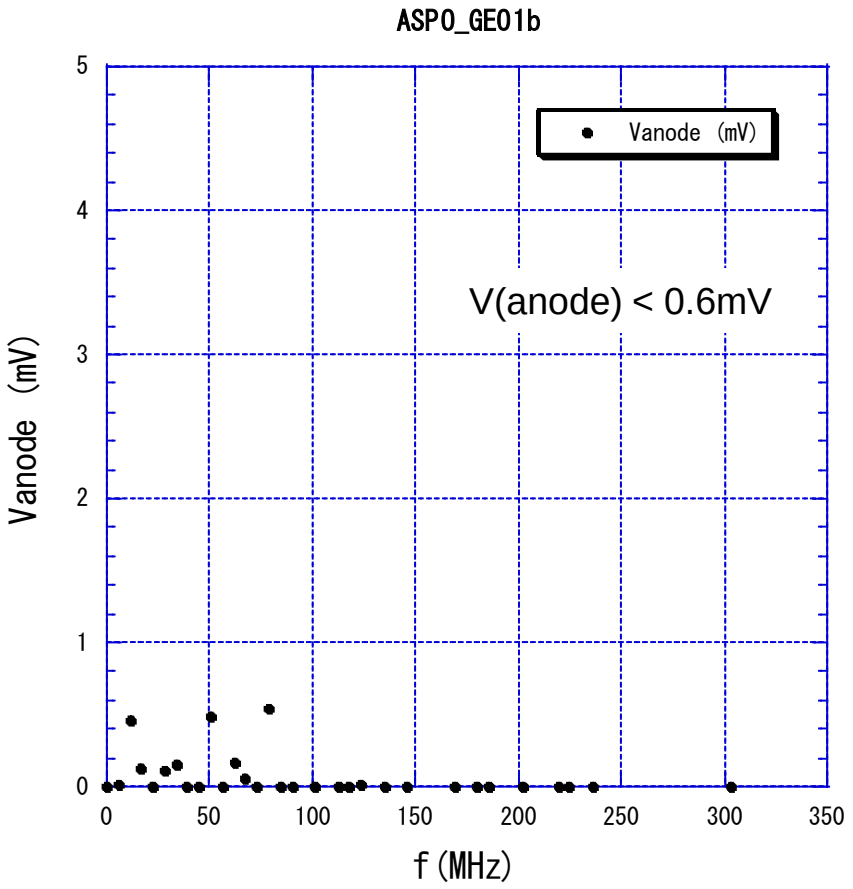

POP1_GE01b
482 mV
(16.881MHz)
V(rf) (mV)
--- POP1 PD: target = 16.880961MHz ---
DC = 5.000748e-02 W
Shot noise = 1.366470e-10 W/rtHz
(10.2 nV/rtHz @16.881MHz)
Zt=87.0 Ω @16.881MHz
V(rf) (mV)
f (MHz)
0
100
200
300
400
500
0
50
100
150
200
250
300
350


POP1_GE01b
Vanode (mV)
V(anode) < 4mV
Vanode (mV)
f (MHz)
0
10
20
30
40
50
0
50
100
150
200
250
300
350

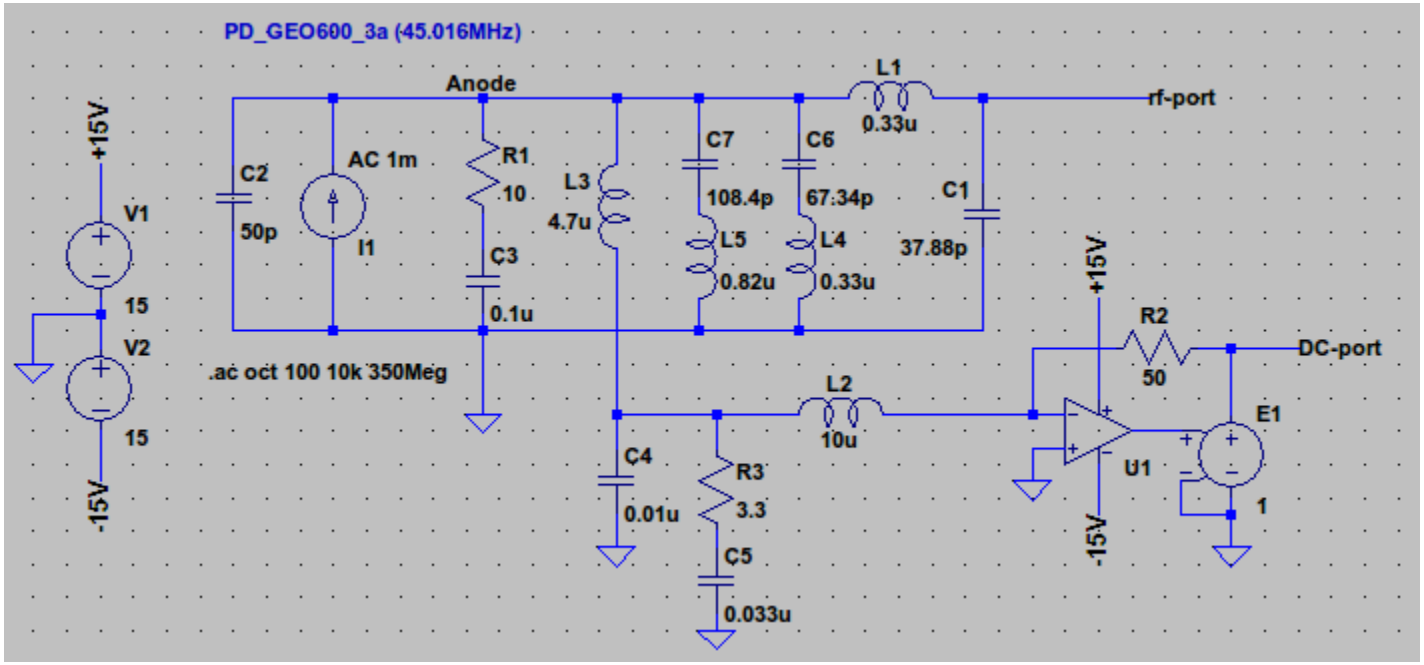

ASPO_power
P (mW)
--- ASPO PD: target = 16.880961MHz ---
DC = 4.208502e-03 W
Shot noise = 3.964115e-11 W/rtHz
P (mW)
f (MHz)
0
1
2
3
4
5
0
50
100
150
200
250
300
350


ASPO_power
Ipd (mA)
光-電流変換効率
0.86 A/W
Ipd (mA)
f (MHz)
0
1
2
3
4
5
0
50
100
150
200
250
300
350

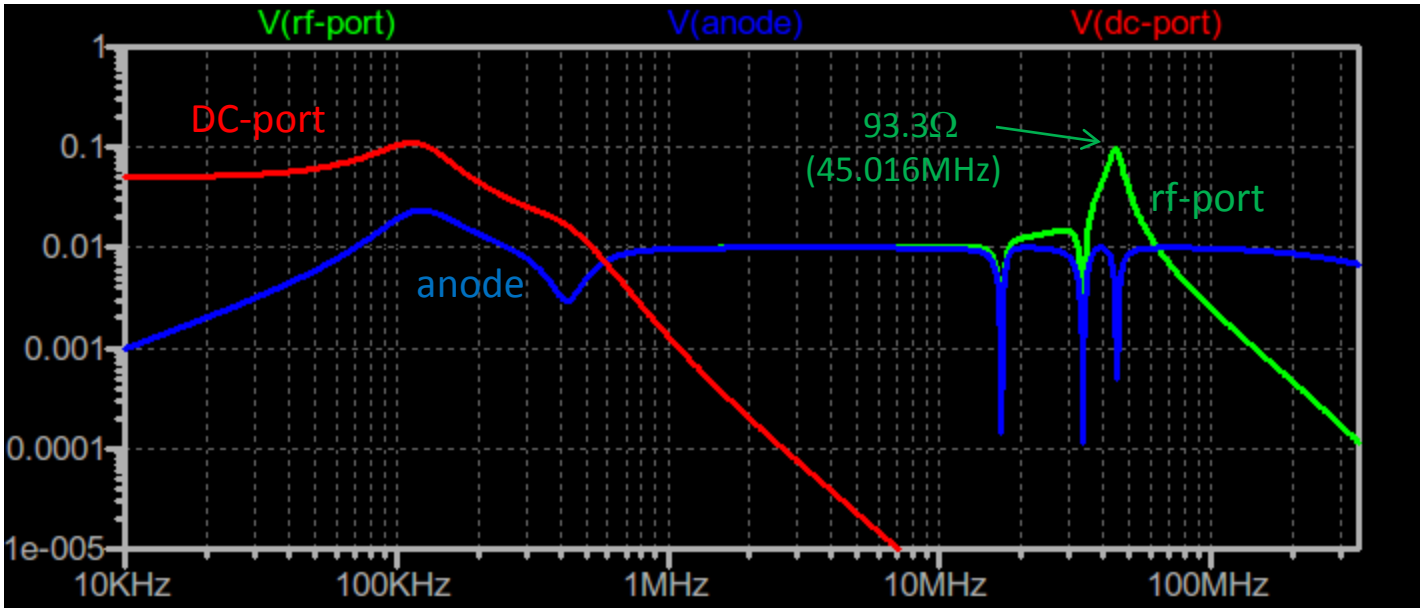

ASPO_GE01b
184 mV
(16.881MHz)
V(rf) (mV)
--- ASPO PD: target = 16.880961MHz ---
DC = 4.208502e-03 W
Shot noise = 3.964115e-11 W/rtHz
(2.97 nV/rtHz @16.881MHz)
Zt=87.0 Ω @16.881MHz
V(rf) (mV)
f (MHz)
0
50
100
150
200
250
300
350

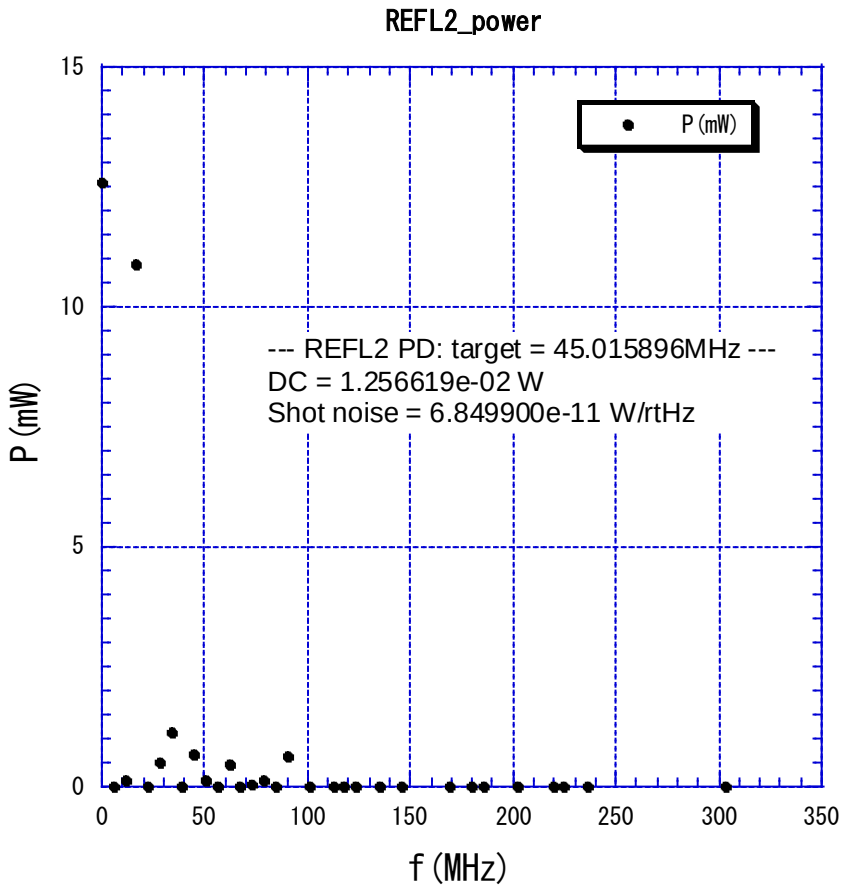

ASPO_GE01b
Vanode (mV)
V(anode) < 0.6mV
Vanode (mV)
f (MHz)
0
1
2
3
4
5
50
100
150
200
250
300
350

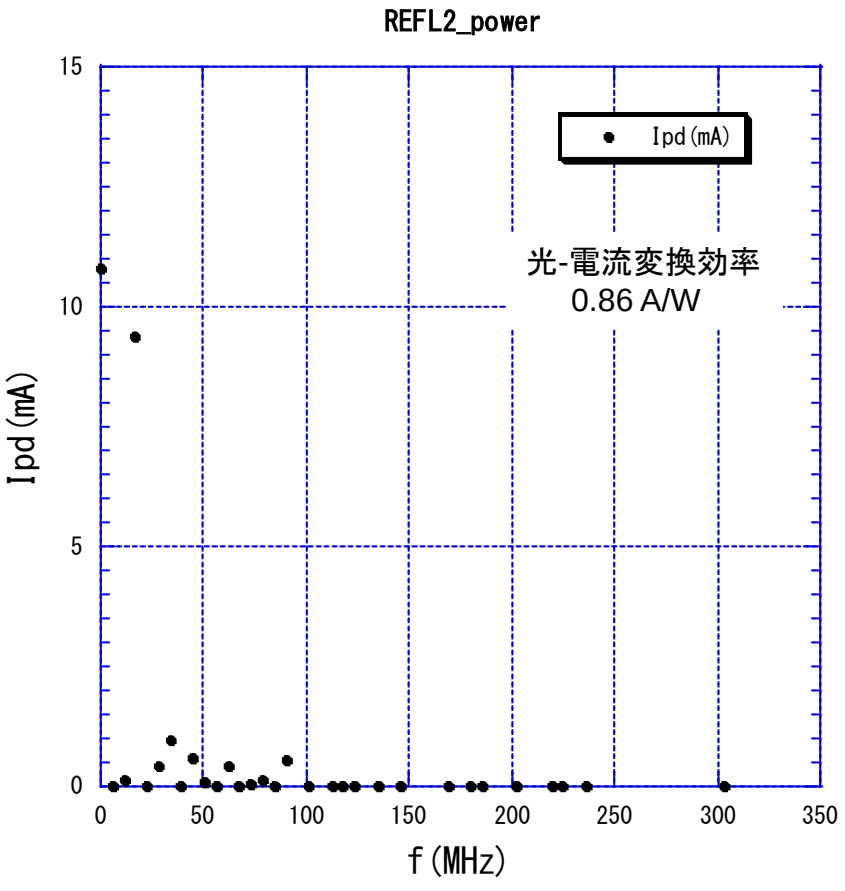
Circuit : GEO600_3a (f_0=45.016MHz : C_{pd}=50pF, L_1=0.82μH, C_1=108.4pF, R_1=10Ω)

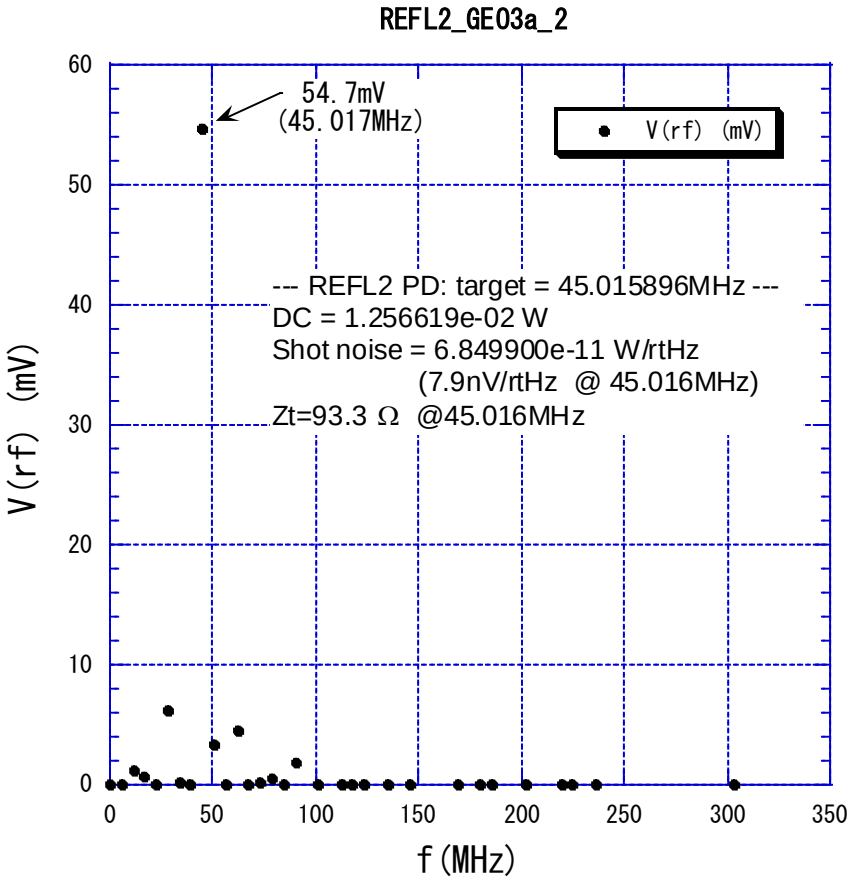


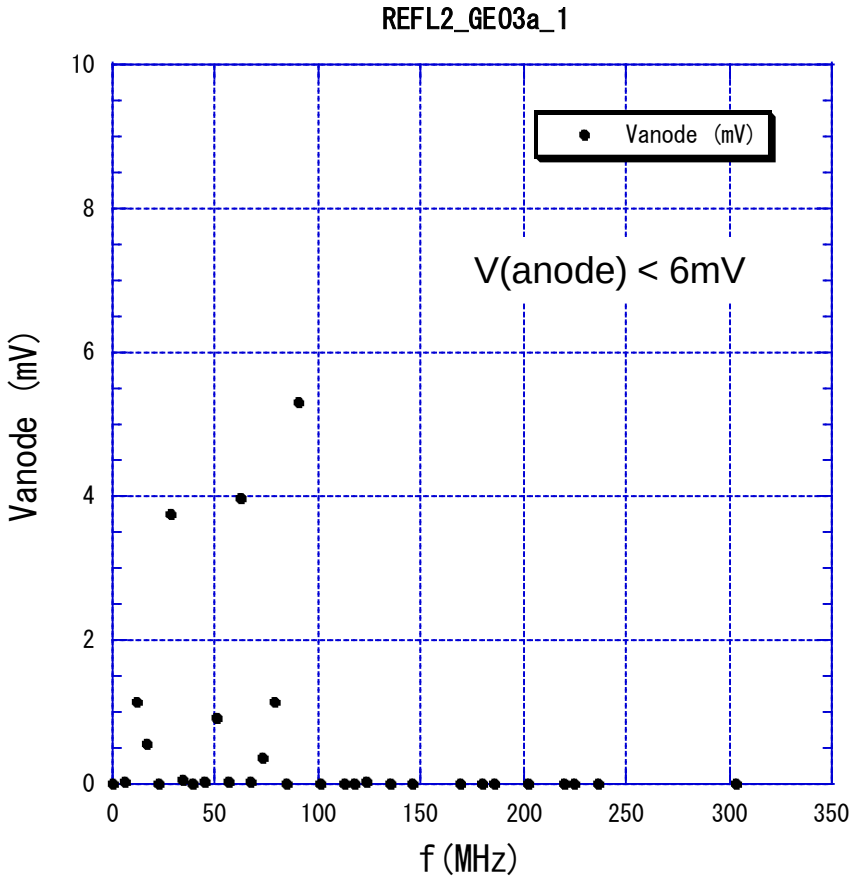
Z_t(kΩ)

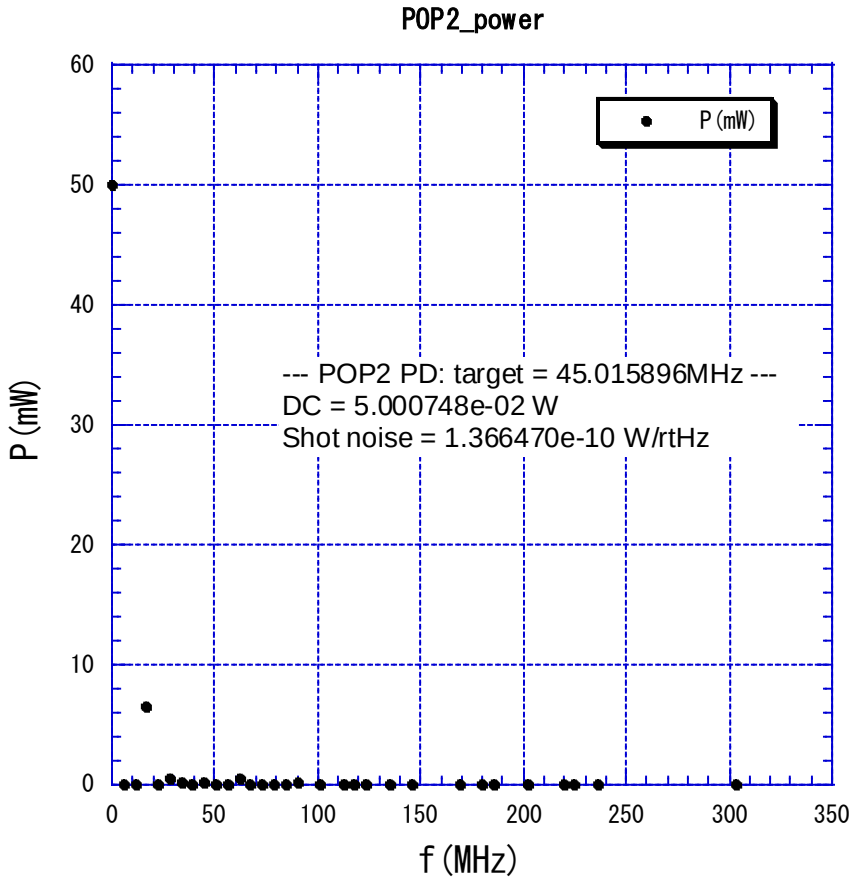


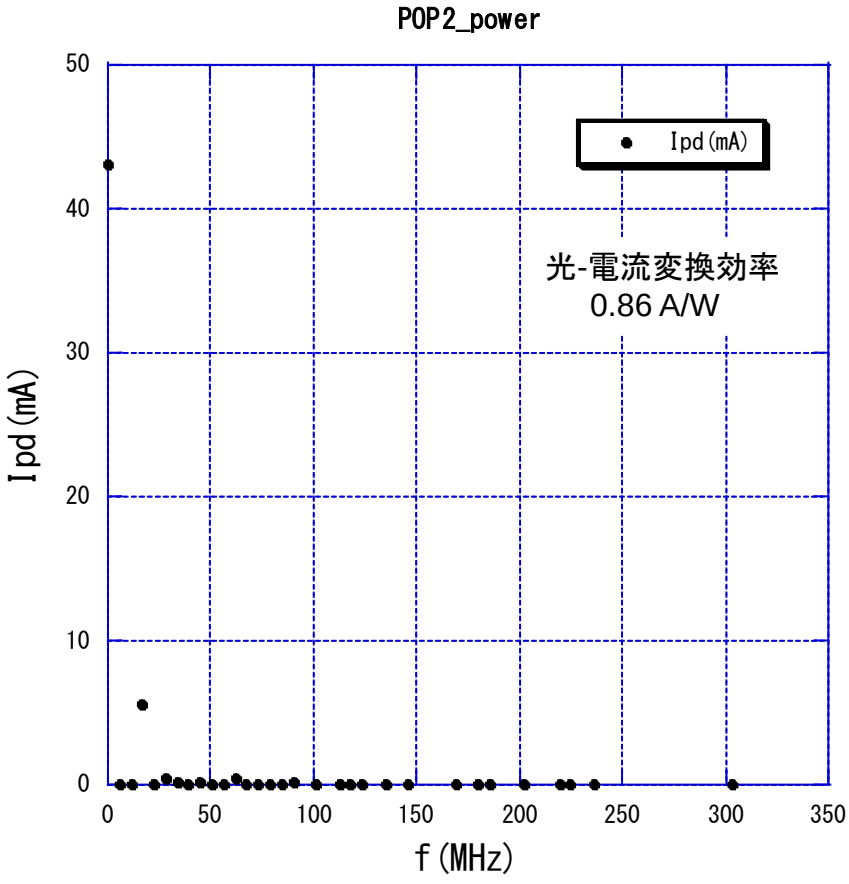

REFL2_power
P (mW)
--- REFL2 PD: target = 45.015896MHz ---
DC = 1.256619e-02 W
Shot noise = 6.849900e-11 W/rtHz
P (mW)
f (MHz)
0
5
10
15
0
50
100
150
200
250
300
350

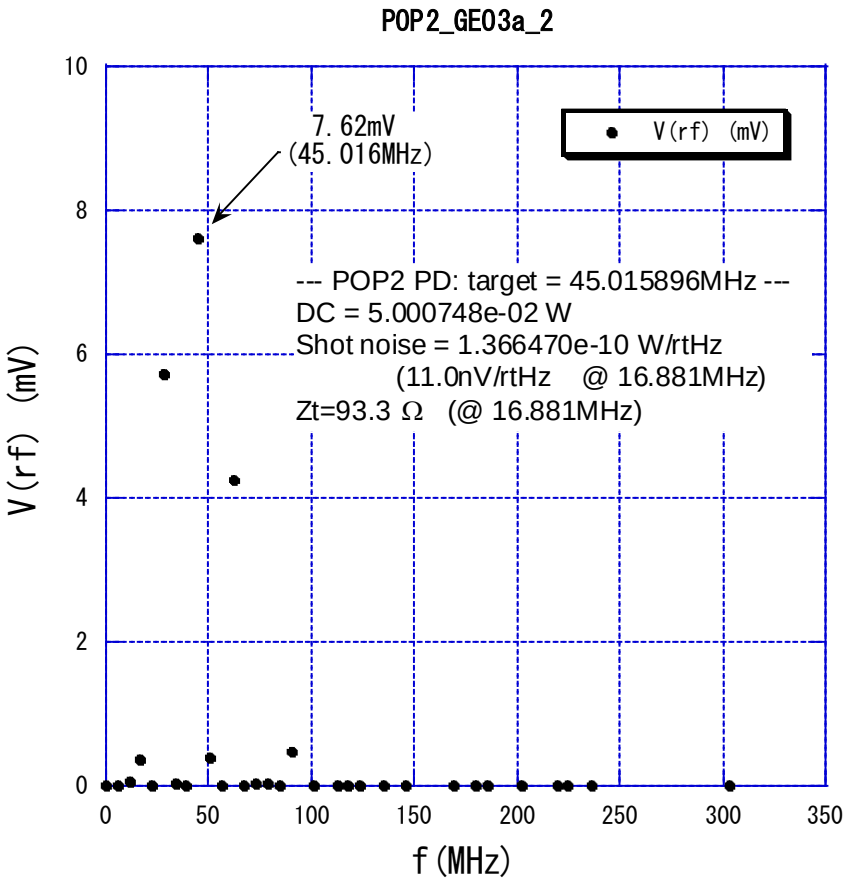

REFL2_power
Ipd (mA)
光-電流変換効率
0.86 A/W
Ipd (mA)
f (MHz)
0
5
10
15
0
50
100
150
200
250
300
350

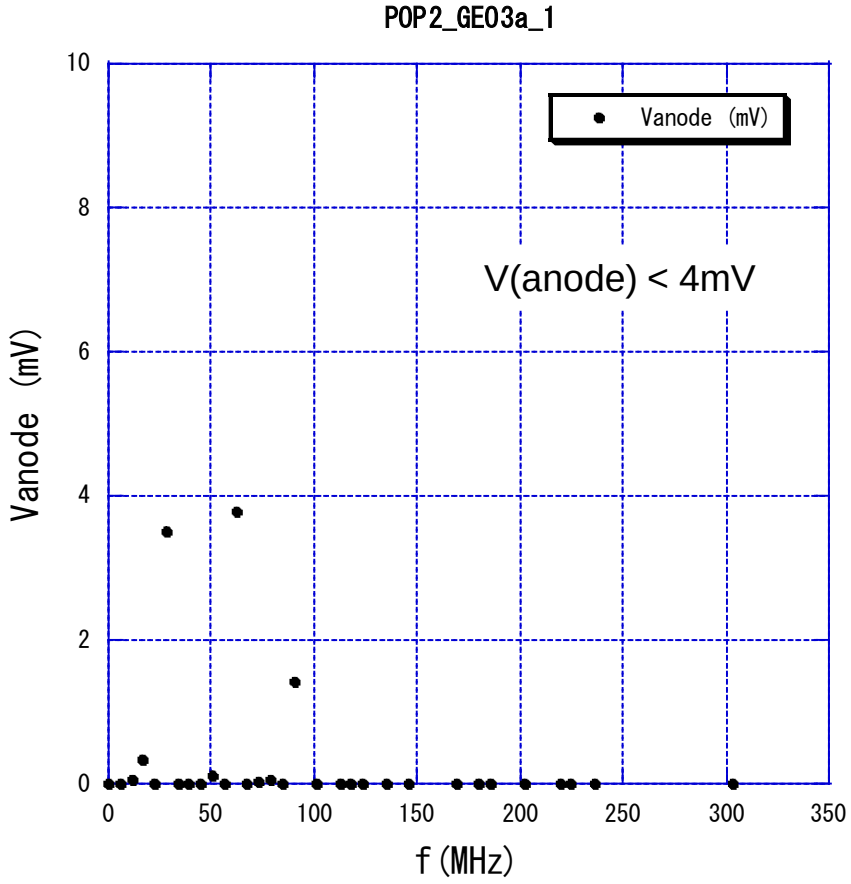

REFL2_GE03a_2
54.7mV
(45.017MHz)
V(rf) (mV)
--- REFL2 PD: target = 45.015896MHz ---
DC = 1.256619e-02 W
Shot noise = 6.849900e-11 W/rtHz
(7.9nV/rtHz @ 45.016MHz)
Zt=93.3 Ω @45.016MHz
V(rf) (mV)
f (MHz)
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350


REFL2_GE03a_1
Vanode (mV)
V(anode) < 6mV
Vanode (mV)
f (MHz)
0
2
4
6
8
10
0
50
100
150
200
250
300
350


POP2_power
P (mW)
--- POP2 PD: target = 45.015896MHz ---
DC = 5.000748e-02 W
Shot noise = 1.366470e-10 W/rtHz
P (mW)
f (MHz)
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350


POP2_power
Ipd (mA)
光-電流変換効率
0.86 A/W
Ipd (mA)
f (MHz)
0
10
20
30
40
50
0
50
100
150
200
250
300
350


POP2_GE03a_2
V(rf) (mV)
f (MHz)
7.62mV
(45.016MHz)
V(rf) (mV)
--- POP2 PD: target = 45.015896MHz ---
DC = 5.000748e-02 W
Shot noise = 1.366470e-10 W/rtHz
(11.0nV/rtHz @ 16.881MHz)
Zt=93.3 Ω (@ 16.881MHz)


POP2_GE03a_1
Vanode (mV)
f (MHz)
Vanode (mV)
V(anode) < 4mV

まとめ（表1）

Target freq.
(circuit resonance freq.)

rf-port 出力用 OP1 の入力
換算雑音はこれより十分小さい
ことが望まれる

$R_1 = 10\,\Omega$
(Appendix B 参照)

Appendix C 参照

PD	circuit	f_0 (MHz)	P (DC) (mW)	P (at f_0) (mW)	Zt (at f_0) (Ω)	V(rf) (mV)	Shot noise (nV/rtHz)	Thermal noise (nV/rtHz)	OP amp noise (nV/rtHz)
REFL1	GEO600_1b (p.2)	16.881	50.265	43.530	87.0	3260	10.3	3.55	2.2 (ADA4899)
REFL2	GEO600_3a (p.9)	45.016	12.566	0.6814	93.3	54.7	5.50	3.80	2.5 (ADA4899)
POP1	GEO600_1b (p.2)	16.881	50.007	6.4403	87.0	482	10.2	3.55	2.2 (ADA4899)
POP2	GEO600_3a (p.9)	45.016	50.007	0.0949	93.3	7.62	11.0	3.80	2.5 (ADA4899)
ASPO	GEO600_1b (p.2)	16.881	4.2085	2.4595	87.0	184	2.97	3.55	2.2 (ADA4899)

at f_0

GEO600_1b : L1=0.82μH, C1=108.4pF, R1=10Ω
GEO600_3a : L1=0.33μH, C1=37.88pF, R1=10Ω

REFL1, ASPO は回路定数の変更可（次ページ表）

注：2012/5/24 麻生氏提供の受光パワー・データ（再計算値）による

まとめ（続）（表２）

REF1, ASPO の回路定数変更

PD	L1 R1 C1	f_0 (MHz)	Zt (at f_0) (Ω)	V(rf) (mV)	Shot noise (nV/rtHz)	Thermal noise (nV/rtHz)	OP amp noise (nV/rtHz)	V(DC) (V)
REFL1	0.68μH 20Ω 130.7pF	16.881	72.1	2700	8.54	2.07	1.2 (ADA4899)	2.16
REFL2	GEO600_3a	45.016	93.3	54.7	5.50	3.80	2.5 (ADA4899)	0.540
POP1	GEO600_1b	16.881	87.0	482	10.2	3.55	2.2 (ADA4899)	2.15
POP2	GEO600_3a	45.016	93.3	7.62	11.0	3.80	2.5 (ADA4899)	2.15
ASPO	1.5μH 20Ω 59.3pF	16.881	159	337	5.43	4.58	3.4 (ADA4899)	0.181

$\omega C_{pd} R_1 << 1$ なる条件のもとでは、REFL2, POP2 (共振周波数45.016MHz) は変更の余地なし

Appendix A 受光パワー （2012/5/26 麻生氏提供）

--- REFL1 PD: target = 16.880961MHz ---
DC = 5.026474e-02 W
Shot noise = 1.369980e-10 W/rtHz
f(MHz), P(W)
5.626987, 1.100485e-05
11.253974, 5.455531e-04
16.880961, 4.352951e-02
22.507948, 1.094440e-06
28.134935, 1.929028e-03
33.761922, 4.533192e-03
39.388909, 2.682817e-07
45.015896, 2.725535e-03
50.642883, 4.731386e-04
56.269870, 1.634270e-05
61.896857, 1.863028e-03
67.523844, 1.356901e-05
73.150831, 1.746389e-04
78.777818, 5.256557e-04
84.404805, 4.551461e-07
90.031792, 2.489756e-03
101.285766, 1.606858e-07
112.539740, 5.254366e-07
118.166727, 5.084316e-06
123.793714, 1.395871e-05
135.047688, 2.613296e-07
146.301662, 2.815484e-09
168.809610, 6.881434e-08
180.063584, 3.166540e-07
185.690571, 5.472501e-09
202.571532, 1.379237e-10
219.452493, 4.854554e-12
225.079480, 1.203652e-11
236.333454, 1.963254e-13
303.857298, 1.287535e-13

--- REFL2 PD: target = 45.015896MHz ---
DC = 1.256619e-02 W
Shot noise = 6.849900e-11 W/rtHz
f(MHz), P(W)
5.626987, 2.751213e-06
11.253974, 1.363883e-04
16.880961, 1.088238e-02
22.507948, 2.736100e-07
28.134935, 4.822570e-04
33.761922, 1.133298e-03
39.388909, 6.707042e-08
45.015896, 6.813838e-04
50.642883, 1.182846e-04
56.269870, 4.085675e-06
61.896857, 4.657570e-04
67.523844, 3.392252e-06
73.150831, 4.365973e-05
78.777818, 1.314139e-04
84.404805, 1.137865e-07
90.031792, 6.224390e-04
101.285766, 4.017145e-08
112.539740, 1.313591e-07
118.166727, 1.271079e-06
123.793714, 3.489677e-06
135.047688, 6.533240e-08
146.301662, 7.038710e-10
168.809610, 1.720358e-08
180.063584, 7.916350e-08
185.690571, 1.368125e-09
202.571532, 3.448092e-11
219.452493, 1.213639e-12
225.079480, 3.009130e-12
236.333454, 4.908134e-14
303.857298, 3.218838e-14

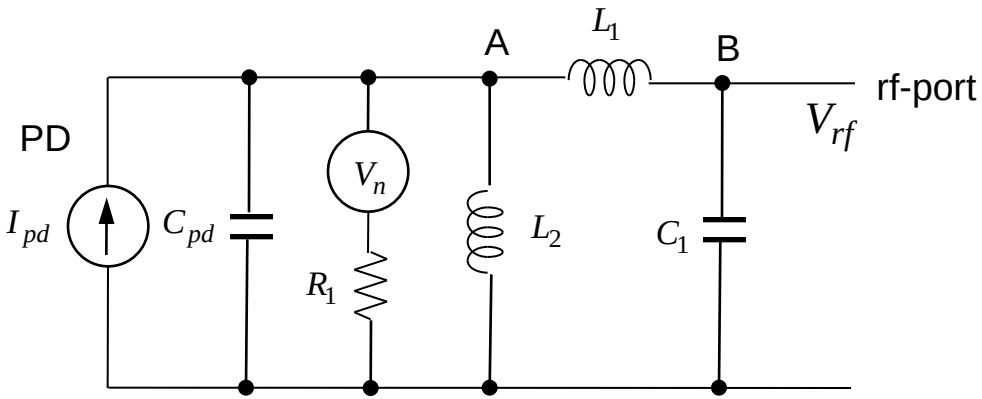
--- POP1 PD: target = 16.880961MHz ---
DC = 5.000748e-02 W
Shot noise = 1.366470e-10 W/rtHz
f(MHz), P(W)
5.626987, 7.733593e-07
11.253974, 6.039889e-06
16.880961, 6.440286e-03
22.507948, 2.040181e-08
28.134935, 4.493085e-04
33.761922, 2.300804e-04
39.388909, 4.504155e-09
45.015896, 9.489546e-05
50.642883, 1.318496e-05
56.269870, 1.099829e-07
61.896857, 4.421604e-04
67.523844, 1.402968e-06
73.150831, 3.098277e-06
78.777818, 6.514071e-06
84.404805, 3.025908e-09
90.031792, 1.672568e-04
101.285766, 3.032683e-09
112.539740, 4.144640e-09
118.166727, 1.807938e-07
123.793714, 1.340232e-07
135.047688, 9.448349e-09
146.301662, 2.201989e-11
168.809610, 1.844614e-09
180.063584, 3.277850e-08
185.690571, 1.384629e-10
202.571532, 9.287771e-13
219.452493, 1.327265e-13
225.079480, 2.499132e-13
236.333454, 4.489983e-16
303.857298, 5.767589e-16

--- POP2 PD: target = 45.015896MHz ---
DC = 5.000748e-02 W
Shot noise = 1.366470e-10 W/rtHz
f(MHz), P(W)
5.626987, 7.733593e-07
11.253974, 6.039889e-06
16.880961, 6.440286e-03
22.507948, 2.040181e-08
28.134935, 4.493085e-04
33.761922, 2.300804e-04
39.388909, 4.504155e-09
45.015896, 9.489546e-05
50.642883, 1.318496e-05
56.269870, 1.099829e-07
61.896857, 4.421604e-04
67.523844, 1.402968e-06
73.150831, 3.098277e-06
78.777818, 6.514071e-06
84.404805, 3.025908e-09
90.031792, 1.672568e-04
101.285766, 3.032683e-09
112.539740, 4.144640e-09
118.166727, 1.807938e-07
123.793714, 1.340232e-07
135.047688, 9.448349e-09
146.301662, 2.201989e-11
168.809610, 1.844614e-09
180.063584, 3.277850e-08
185.690571, 1.384629e-10
202.571532, 9.287771e-13
219.452493, 1.327265e-13
225.079480, 2.499132e-13
236.333454, 4.489983e-16
303.857298, 5.767589e-16

--- ASPO PD: target = 16.880961MHz ---
DC = 4.208502e-03 W
Shot noise = 3.964115e-11 W/rtHz
f(MHz), P(W)
5.626987, 1.241853e-06
11.253974, 5.505002e-05
16.880961, 2.459520e-03
22.507948, 5.904967e-08
28.134935, 1.523102e-05
33.761922, 4.022986e-03
39.388909, 2.609744e-08
45.015896, 9.510846e-05
50.642883, 6.302600e-05
56.269870, 8.259401e-07
61.896857, 1.931459e-05
67.523844, 5.876853e-06
73.150831, 5.929963e-07
78.777818, 6.283580e-05
84.404805, 2.420282e-08
90.031792, 5.821271e-07
101.285766, 1.368103e-08
112.539740, 5.183023e-08
118.166727, 1.998011e-09
123.793714, 1.122259e-06
135.047688, 1.547713e-08
146.301662, 9.693689e-11
168.809610, 5.734567e-11
180.063584, 1.889478e-10
185.690571, 8.266513e-10
202.571532, 1.583382e-11
219.452493, 1.158499e-13
225.079480, 1.728828e-15
236.333454, 1.130181e-14
303.857298, 1.152063e-17

Appendix B　等価回路

B点（OP1入力）までの等価回路、トラップは省略



$$V_A(\omega) = Z_t^{anode}(\omega)(I_{pd} + V_n / R_1)$$

$$V_B(\omega) = Z_t^{rf}(\omega)(I_{pd} + V_n / R_1)$$

$$Z_t^{rf}(\omega) = \frac{j\omega L_2}{1-\omega^2(L_1+L_2)C_1 + (j\omega L_2 / R_1)(1-\omega^2 L_1 C_1)(1+ j\omega C_{pd} R_1)}$$

$$Z_t^{anode}(\omega) = Z_t^{rf}(\omega)(1-\omega^2 L_1 C_1)$$

$Z_t^{anode}(\omega)$ は I_{pd} に対するA点における伝達インピーダンス（trans-impedance)

$Z_t^{rf}(\omega)$ は I_{pd} に対するB点における伝達インピーダンス

＊ L_1 、C_1 の共振周波数 $\omega = \omega_0 = 1/\sqrt{L_1 C_1}$ では、共振の Q 値

$$Q = \frac{\omega_0 L_1}{R_1} = \frac{1}{\omega_0 C_1 R_1}$$

を用いて

$$Z_t^{rf}(\omega_0) = QR_1 = 1/\omega_0 C_1 = \omega_0 L_1$$ （$Z_t^{rf}(\omega_0)$ は L_1 または C_1 のみで決まる）

$$V_{rf}(\omega_0) = -jZ_t^{rf}(\omega_0) I_{pd} - jQV_n$$

となる。

＊ L_1 、C_1 の共振特性を乱さないためには

$\omega C_{pd} R_1 << 1$

であることが必要（ $C_{pd} = 50pF, R_1 = 10\Omega \rightarrow \omega C_{pd} R_1 = 0.157\,(at\ 50MHz)$ ）

$R_1 > 15\Omega$ では C_{pd} の影響による共振周波数のずれが顕著になる

＊ V_n を R_1 の抵抗熱雑音 $V_n = \sqrt{4kTR_1\Delta f}$ とすると

B点に生ずる熱雑音は

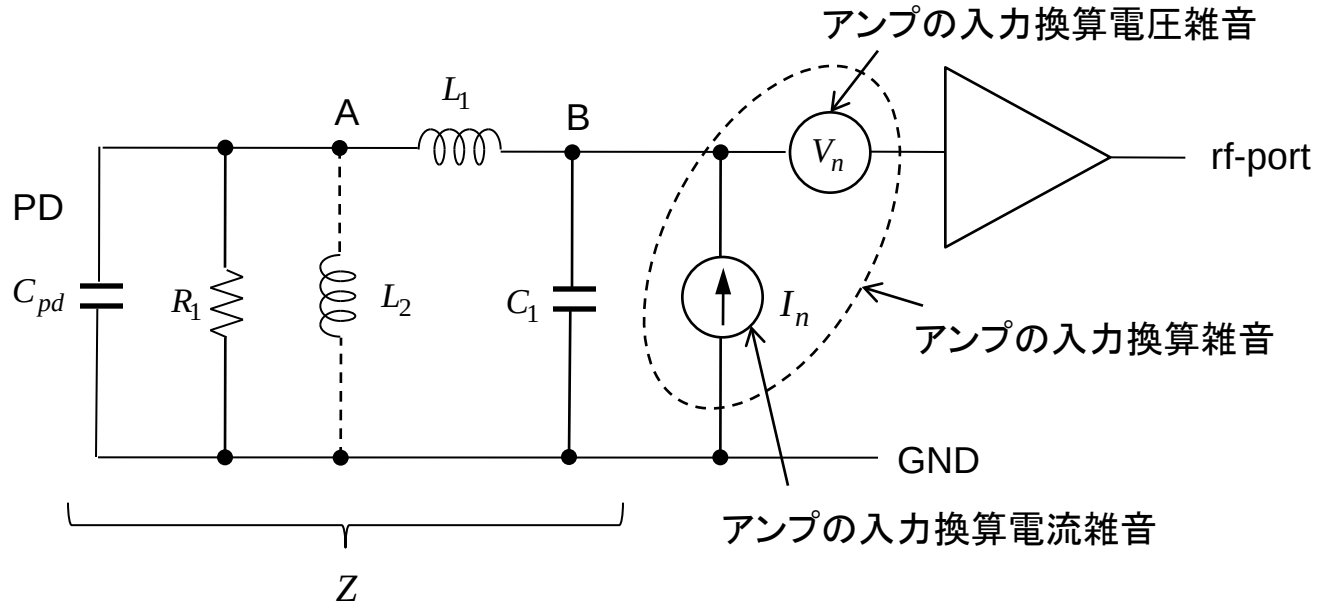
$$QV_n = \frac{Z_t^{rf}(\omega_0)}{R_1} V_n = Q\sqrt{4kTR_1\Delta f}$$ である

I_{pd} に対して熱雑音を下げるには QR_1 を大きくする → C_1 が小さくなる

→ OP_1 の入力容量の影響が大きくなる（あまり自由度はない）

$R_1 = 10\,\Omega$ p.14

Appendix C　rf-port オペアンプの雑音



アンプの入力から見た回路のインピーダンスを$Z(\omega)$ として、アンプ入力換算雑音電圧V_{nT} は

$$V_{nT}^2 = V_n^2 + \left|Z(\omega)\right|^2 I_n^2$$

L_1 、C_1 の共振周波数 $\omega_0 = 1/\sqrt{L_1 C_1}$ 近傍では$\omega L_2 >> R_1$ であるとするとL_2 は無視できて

$$Z(\omega_0) = \frac{j\omega L_1 + R_1}{j\omega C_1 R_1} = Q(Q - j)R_1 \quad \rightarrow \quad \left|Z(\omega_0)\right| = Q\sqrt{Q^2 + 1}R_1 \approx QZ_t$$

（ $Q = \omega L_1 / R_1$ は L_1 、C_1 、R_1 から成る直列共振回路のQ値）

オペアンプ

LMH6609 (National Semiconductor)

$V_n = 3.1\,nV/\sqrt{Hz}, \quad I_n = 1.6\ pA/\sqrt{Hz}$

$$\begin{cases} R_1 = 10\Omega,\ Z_t = 87.0\Omega \rightarrow & V_{nT} = 3.3nV/\sqrt{Hz} \\ R_1 = 10\Omega,\ Z_t = 93.3\Omega \rightarrow & V_{nT} = 3.4nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 72.1\Omega \rightarrow & V_{nT} = 3.1nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 159\Omega \rightarrow & V_{nT} = 3.7nV/\sqrt{Hz} \end{cases}$$

LMH6628 (National Semiconductor)

$V_n = 2\,nV/\sqrt{Hz}, \quad I_n = 2\ pA/\sqrt{Hz}$

$$\begin{cases} R_1 = 10\Omega,\ Z_t = 87.0\Omega \rightarrow & V_{nT} = 2.5nV/\sqrt{Hz} \\ R_1 = 10\Omega,\ Z_t = 93.3\Omega \rightarrow & V_{nT} = 2.7nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 72.1\Omega \rightarrow & V_{nT} = 2.1nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 159\Omega \rightarrow & V_{nT} = 3.2nV/\sqrt{Hz} \end{cases}$$

AD8000 (Analog Devices)

$V_n = 1.6\,nV/\sqrt{Hz}, \quad I_n = 3.4\ pA/\sqrt{Hz}$

$$\begin{cases} R_1 = 10\Omega,\ Z_t = 87.0\Omega \rightarrow & V_{nT} = 3.0nV/\sqrt{Hz} \\ R_1 = 10\Omega,\ Z_t = 93.3\Omega \rightarrow & V_{nT} = 3.4nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 72.1\Omega \rightarrow & V_{nT} = 1.8nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 159\Omega \rightarrow & V_{nT} = 4.6nV/\sqrt{Hz} \end{cases}$$

ADA4899-1 (Analog Devices)

$V_n = 1\,nV/\sqrt{Hz}, \quad I_n = 2.6\ pA/\sqrt{Hz}$

$$\begin{cases} R_1 = 10\Omega,\ Z_t = 87.0\Omega \rightarrow & V_{nT} = 2.2nV/\sqrt{Hz} \\ R_1 = 10\Omega,\ Z_t = 93.3\Omega \rightarrow & V_{nT} = 2.5nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 72.1\Omega \rightarrow & V_{nT} = 1.2nV/\sqrt{Hz} \\ R_1 = 20\Omega,\ Z_t = 159\Omega \rightarrow & V_{nT} = 3.4nV/\sqrt{Hz} \end{cases}$$