A New Figure of Merit of LC Oscillators Considering Frequency Tuning Range

Takahiro Sato, Kenichi Okada,
and Akira Matsuzawa

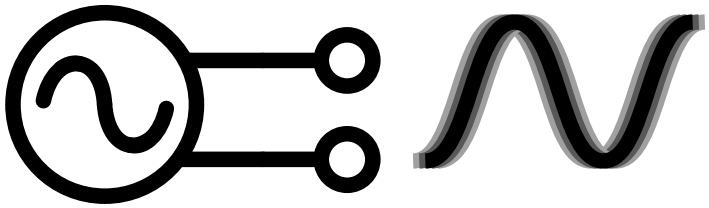
Tokyo Institute of Technology, Japan

2011/10/26

Outline

- Background
- The effect of FTR
- Defining new FoM
- Comparing between the new and old FoM
- Summary

Specifications



Output Frequency？
Phase Noise？
Power Consumption？

Figure of Merit Difinition

$$\mathrm{FoM} = \mathcal{L}(f_{\mathrm{offset}}) - 20\log_{10}\left(\frac{f_0}{f_{\mathrm{offset}}}\right) + 10\log_{10}\left(\frac{P_{\mathrm{DC}}}{1\mathrm{mW}}\right)$$ [1]

$\mathcal{L}$:Phase Noise	P_{DC}:Power Consumption
f_0:Oscillating Frequency	f_{offset}:Offset Frequency

Evaluates performance at ONE frequency only.

Frequency Tuning Range (FTR) is not included

[1] P.Kinget 1999

Conventional FoM Including FTR

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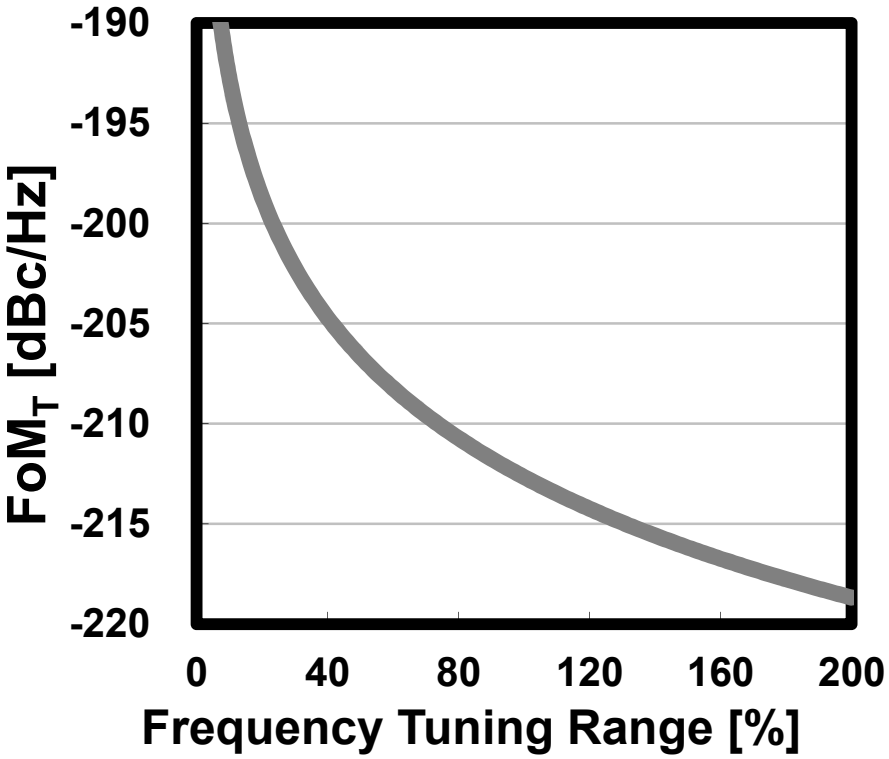
Conventional FoM Including FTR

$$\mathrm{FoM_T} = \mathrm{FoM_{peak}} - 20\log_{10}\left(\frac{FTR}{0.1}\right) \quad \textbf{[2]}$$

$$FTR = (f_{\max} - f_{\min})/f_{\mathrm{center}}$$



ex)
FTR=0[%] ⇒ $\mathrm{FoM_T}$=+∞ [dBc/Hz]

FTR=4[%] ⇒ $\mathrm{FoM_T}$=-184[dBc/Hz]
FTR=12[%] ⇒ $\mathrm{FoM_T}$=-194[dBc/Hz]
Delta:10[dBc/Hz]

etc.

Not Fair !!!

New FoM is needed.

[2] J.Kim, *et al.*, ISSCC 2005

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LC Oscillators and Q-factor

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$$\mathrm{FoM} = \mathcal{L}(f_{\mathrm{offset}}) - 20\log_{10}\left(\frac{f_0}{f_{\mathrm{offset}}}\right) + 10\log_{10}\left(\frac{P_{\mathrm{DC}}}{1\mathrm{mW}}\right)$$

$$\mathcal{L}(f_{\mathrm{offset}}) = 10\log_{10}\left[\frac{2FkT}{P_{\mathrm{sig}}}\frac{f_0^2}{4Q^2 f_{\mathrm{offset}}}\right] \quad \text{[3]}$$

$$\mathrm{FoM} = 10\log_{10}\left[\frac{FkT}{2\mathrm{mW}}\frac{P_{\mathrm{DC}}}{P_{\mathrm{sig}}Q^2}\right]$$

F:Device excess noise number
k:Boltzmann constant
T:Absolute temperature
P_{sig}:Output power
Q:Quality factor of LC tank

The Q-factor of capacitors are sufficiently higher than that of an inductor, at frequencies less than or equal 10GHz.

$$Q = \frac{Q_{\mathrm{L}} \cdot Q_{\mathrm{C}}}{Q_{\mathrm{L}} + Q_{\mathrm{C}}} \approx Q_{\mathrm{L}}$$

The performance of LC oscillators is decided by Q-factor of the inductor.

[3]A.Hajimiri JSSC1998

Q-factor and FTR

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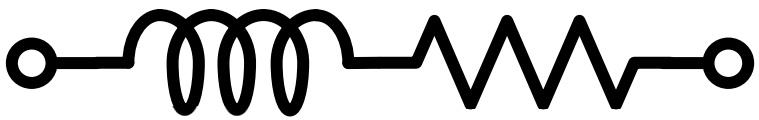
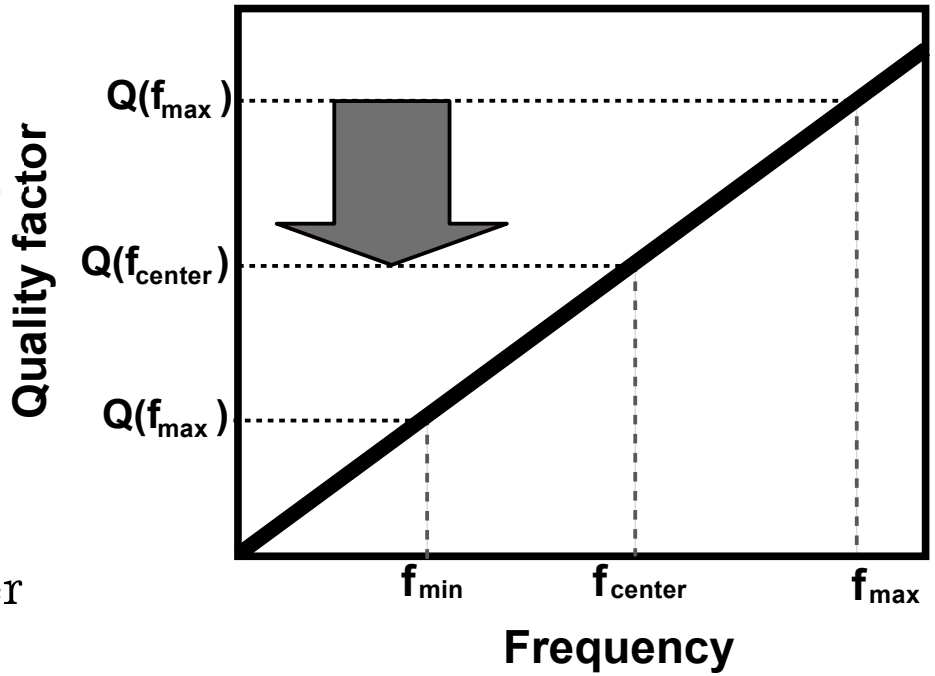


L R_L:internal resistance

$$Q_L = \frac{2\pi f L}{R_L}$$



- **Definition of FTR**

$$FTR = (f_{\max} - f_{\min}) / f_{\text{center}}$$

$$\therefore \quad Q(f_{\max}) = Q(f_{\text{center}}) \cdot \left(1 + \frac{FTR}{2}\right)$$

Maximum Q-factor is defined in terms of the FTR and Q-factor at the center frequency.

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The New FoM

By substituting the formula of FTR and center freq Q-factor into the FoM definition, the new FoM, called $\mathrm{FoM_L}$, is defined as follows.

$$\mathrm{FoM_L} \equiv 10\log_{10}\left[\frac{FkT}{2mW}\frac{P_{DC}}{P_{sig}\cdot\left\{Q(f_{center})\cdot\left(1+\frac{FTR}{2}\right)\right\}^2}\right]$$

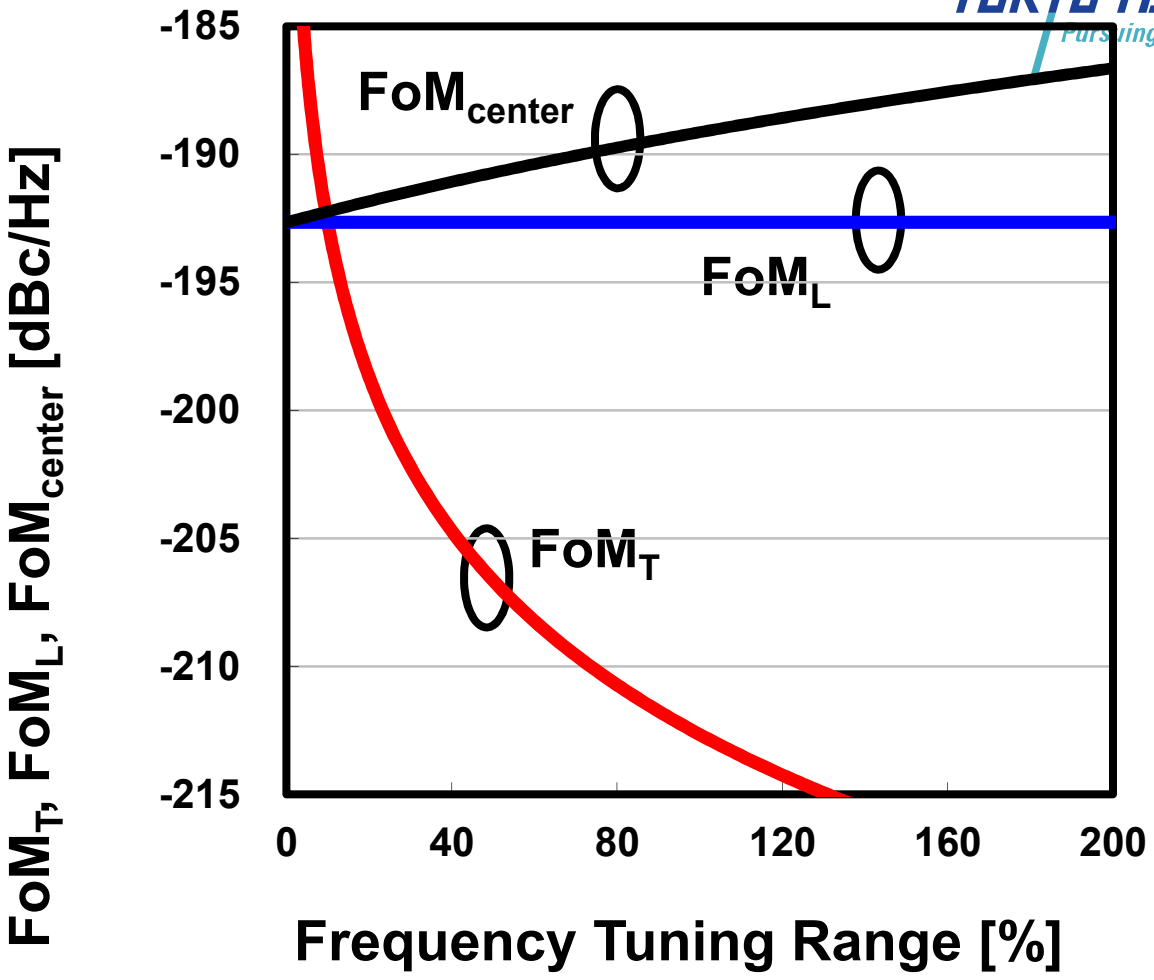
$Q(f_{max})$

FoM Including FTR

$$\mathrm{FoM_L} = \mathrm{FoM}(f_{center}) - 20\log_{10}\left(1+\frac{FTR}{2}\right)$$

Numerical Comparison

$$Q(f_{\max}) = 10$$
$$T = 300[\mathrm{K}]$$
$$F = 1 + 2/3$$



As FTR widens:

- FoM_L:no change → valid comparison
- FoM_T:too low → estimates that a wide FTR oscillator is better

Simulation Setup

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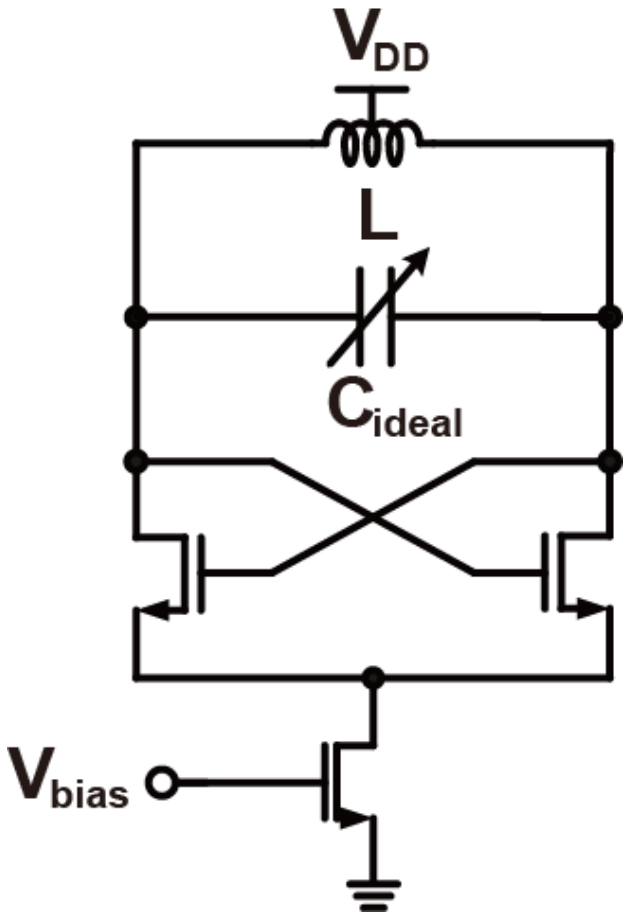
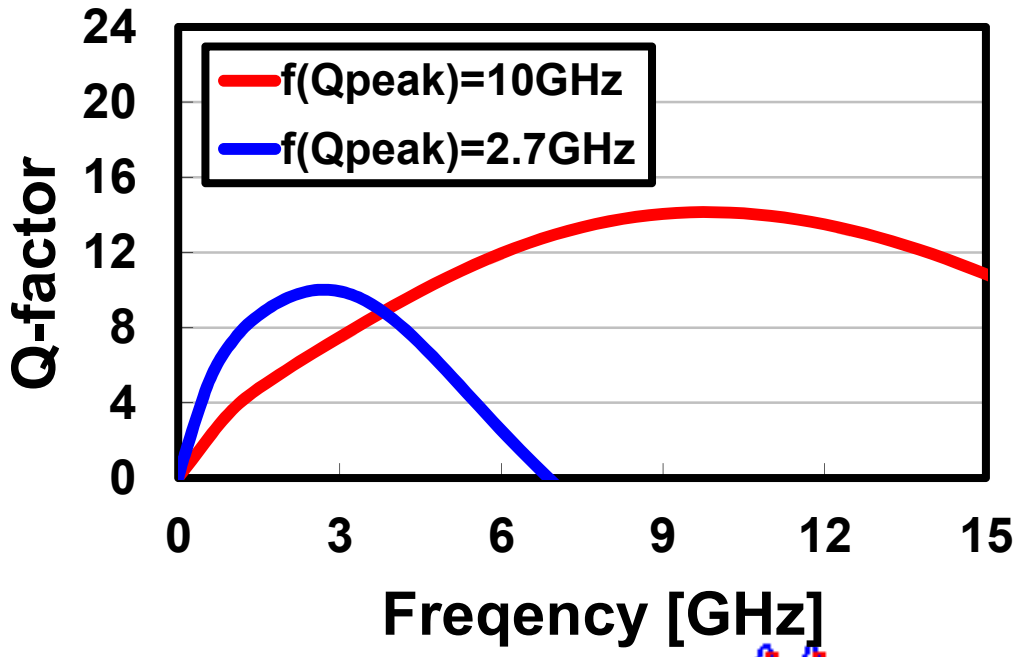
- Si CMOS 0.18μm proccess
- NMOS cross couple
- The capacitance is ideal



- Inductor specifications:

	Inductor 1	Inductor 2
Inductance [nH]	1.77	5.23
Freq of Q_{peak} [GHz]	10.1	2.7
Q_{peak}	14	11



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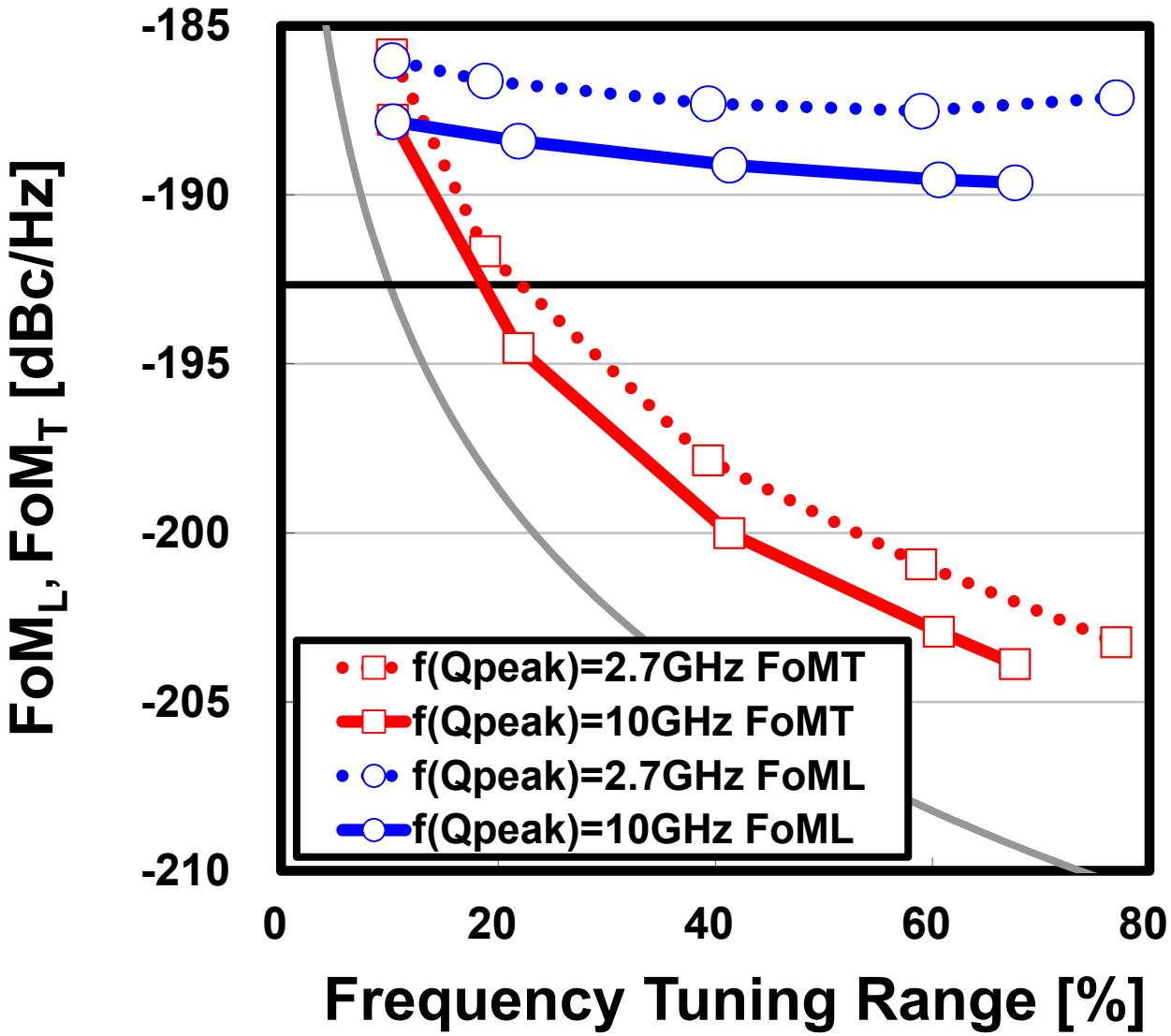
Simulation Result



Theoretical curves tend to be in agreement with simulation results.

Paper Comparison

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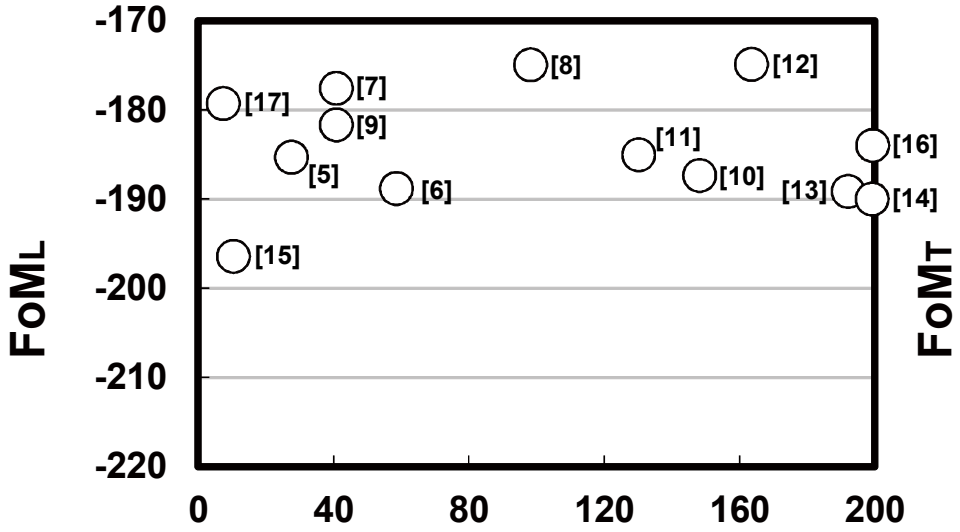

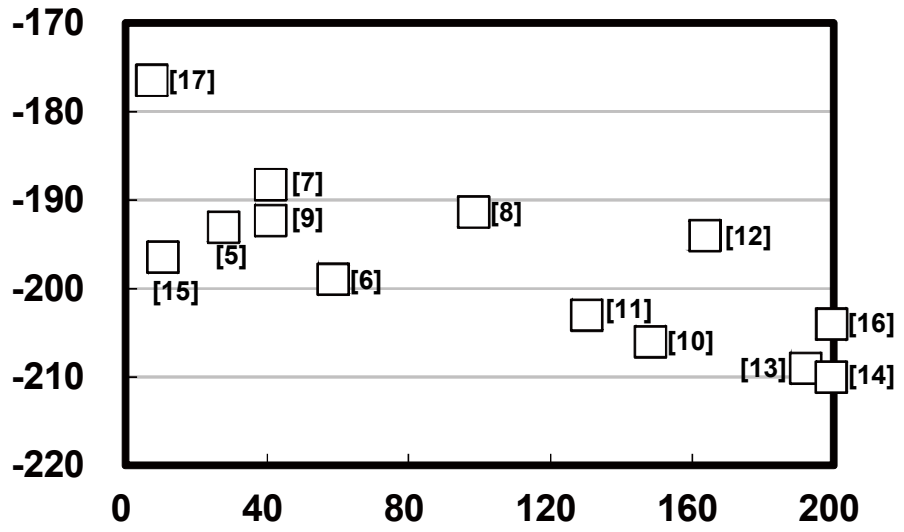

FoM_L takes the effect of the deterioration in the average Q into consideration and remains relatively constant.

[5] A.D.Bemy, *et al*., CICC 2003 [6] N.H.W.Fong, *et al*,. JSSC 2003 [7] A. Fard, *et al*., Radio and Wireless Conference 2004
[8] D. Guermandi, *et al*., ISSCC 2005 [9] A. Fard, ISCAS 2005 [10] Y. Ito, *et al*., ASSCC 2006 [11] Z. Safarian, *et al*., CICC 2008
[12] B. Razavi, VLSI 2009 [13] V. Giannini, *et al*., ISSCC 2009 [14] S. Hara, *et al*., ASSCC 2009 [15] A. Mazzanti, JSSC 2009
[16] S. Hara, *et al*.,VLSI 2010 [17] U. Decanis, *et al*., ISSCC 2011

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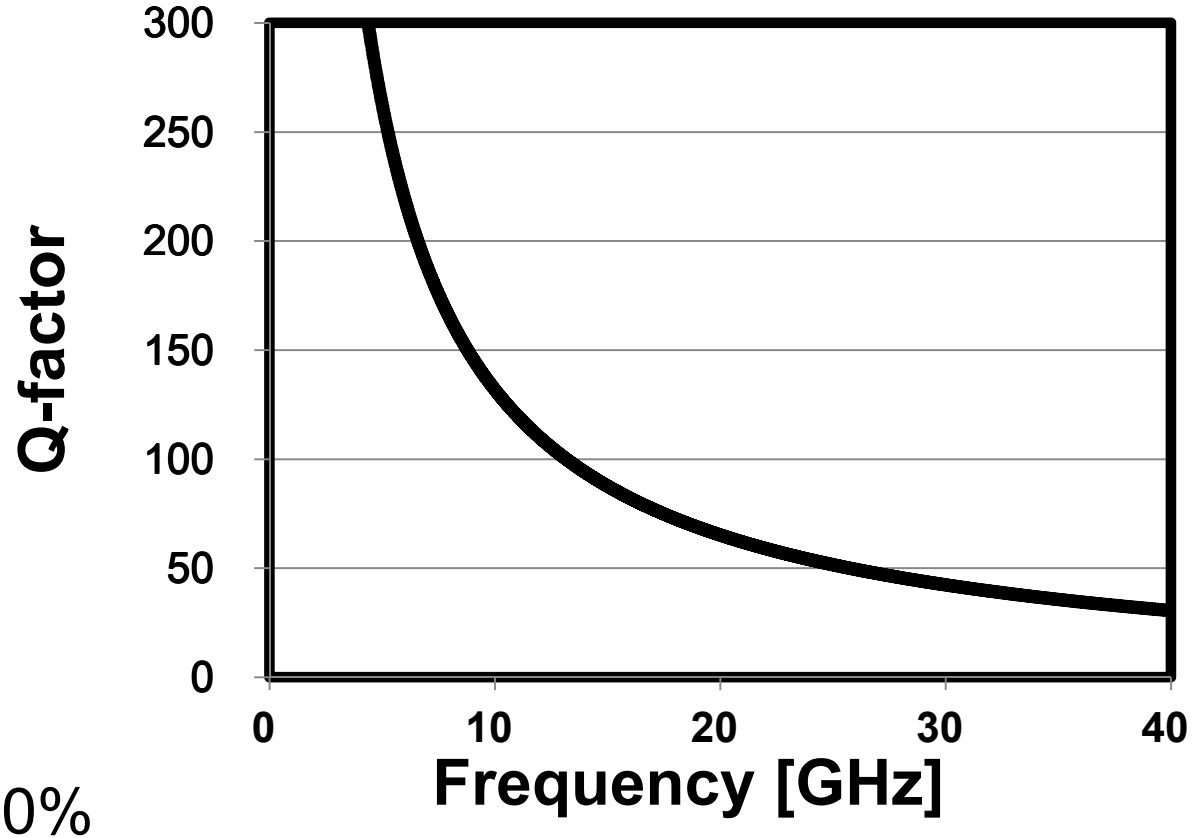
Summary

- A new FoM of LC oscillators that includes Frequency Tuning Range (FTR) is defined.

- Simulation results and paper comparison were used to confirm the validity of the proposed FoM where it was found that it gives a better figure of merit for comparing the performance of VCOs.

Q-factor of capacitor



FTR=40%

Frequency [GHz]	Q_C	差分FoM (Q_L=15) [dBc/Hz]
10	132	0.9
15	88	1.4
20	65	1.8