8th INTERNATIONAL CONGRESS ICICT 2023
20-23 February, 2023 London / UK

Design Consideration for LC Analog Filters: Inductor ESR Compensation, Mutual Inductance Effect and Variable Center Frequency

Misaki Takagi, T. Nakatani, S. Katayama, D. Iimori, G. Ogihara, Y. Zhao, A. Kuwana, K. Sato, T. Ishida, T. Okamoto, T. Ichikawa, K. Katoh, K. Hatayama, H. Kobayashi

群馬大学
GUNMA UNIVERSITY

Gunma University
Rohm Semiconductor

Kobayashi Laboratory

OUTLINE

- Research Background
- Approach
  - Inductor ESR Compensation
  - Application to LC BPF
  - Application to LC BEF
  - Application to Variable Inductor Realization
- Conclusion

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Research Background

Analog/mixed-signal IC testing systems

- Low distortion sine wave generation
- Total Harmonic Distortion (THD) measurement

Key components

→ Analog Band Pass Filter (BPF)
and Band Elimination Filter (BEF)

Using dedicated devices

Superior performance

Very costly

Using standard discrete components

→ Reasonable

Research Objective

Using inductors on shelf

Realization of { low cost, good performance } LC BPF, BEF

For this purpose

Inductor ESR compensation technique

ESR: Equivalent Series Resistance

+

Parasitic mutual inductor effects, Countermeasure

- Variable inductor realization
- Variable center frequency BPF, BEF

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Approach

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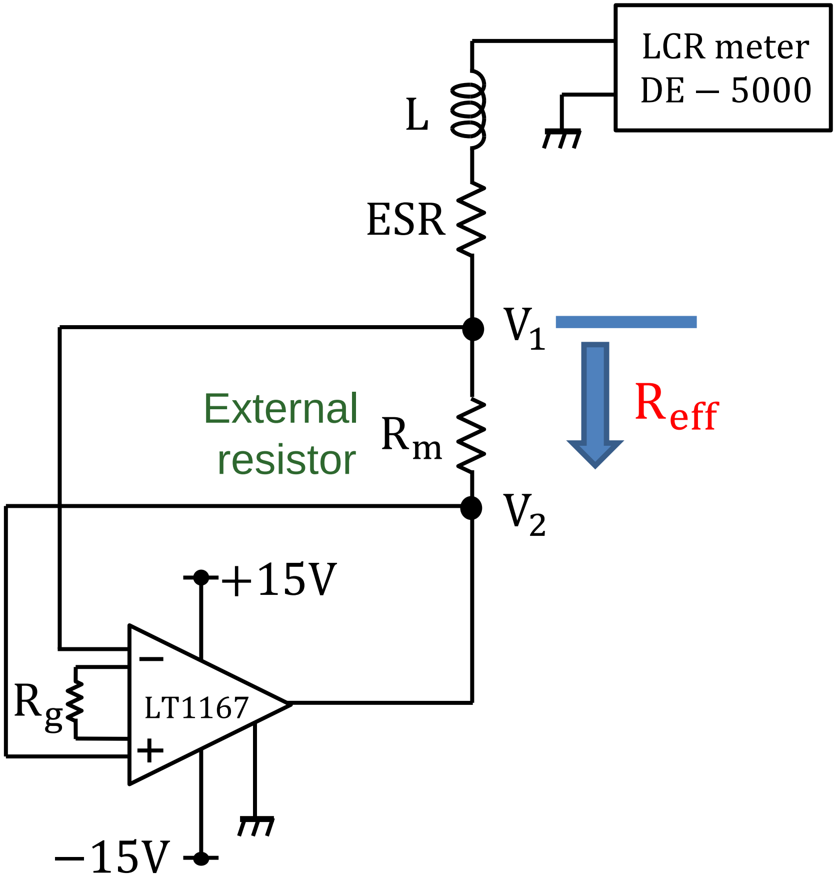
Inductor ESR Compensation



Gain G ➡ Controllable by resistor R_g

$$V_2 = G(V_2 - V_1)$$

$$R_m I = V_1 - V_2 = \frac{V_2}{1 - G}$$

Effective resistor from node V_1

$$R_{eff} = \frac{V_1}{I} = (1 - G)R_m$$

$R_{eff} < 0$ for $G > 1$

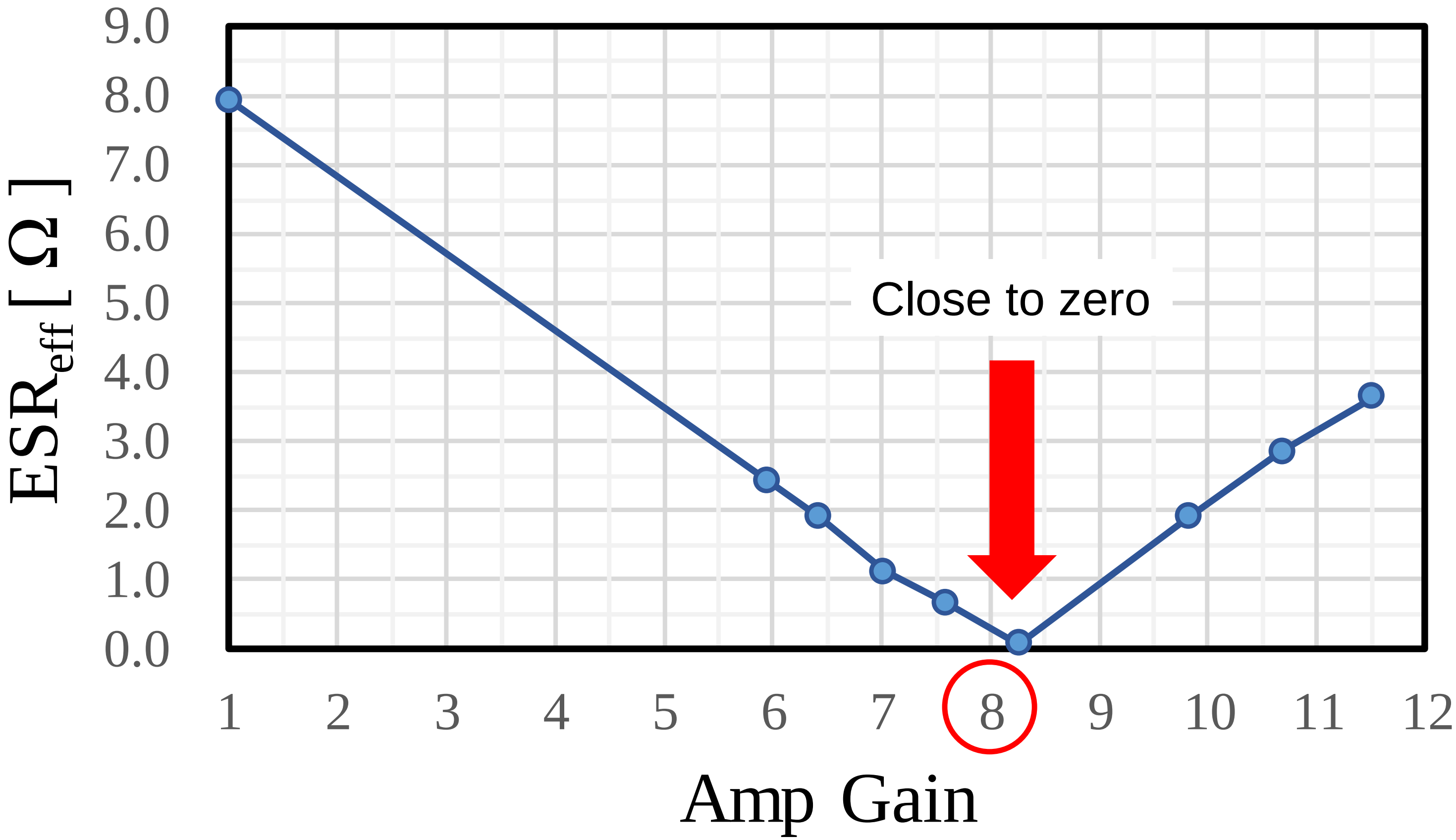
Effective ESR

$$ESR_{eff} = ESR + R_{eff} \Rightarrow 0$$

By adjusting G,
negative effective resistance R_{eff}
cancels ESR.

Measurement Verification

Proposed inductor ESR compensation measured result



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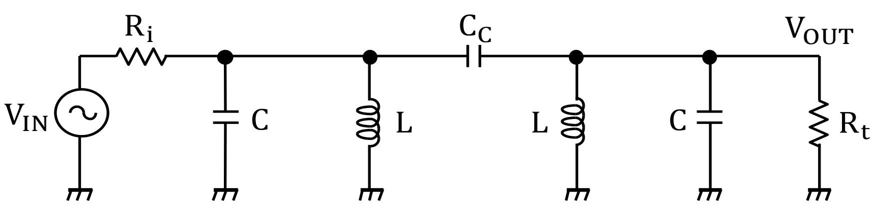
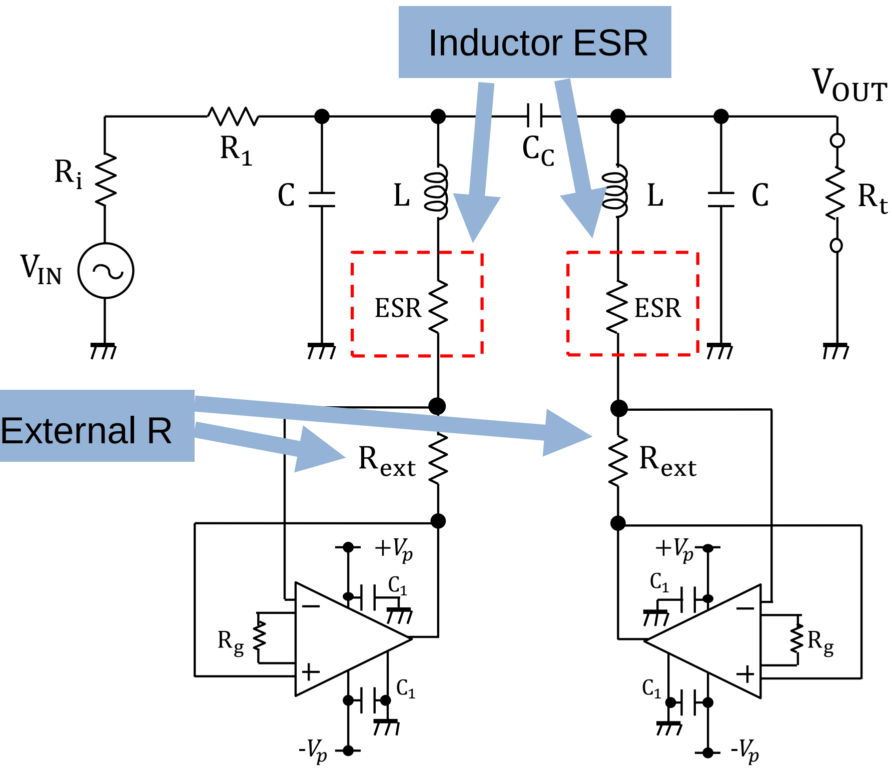
Application to LC BPF



Ideal LC BPF

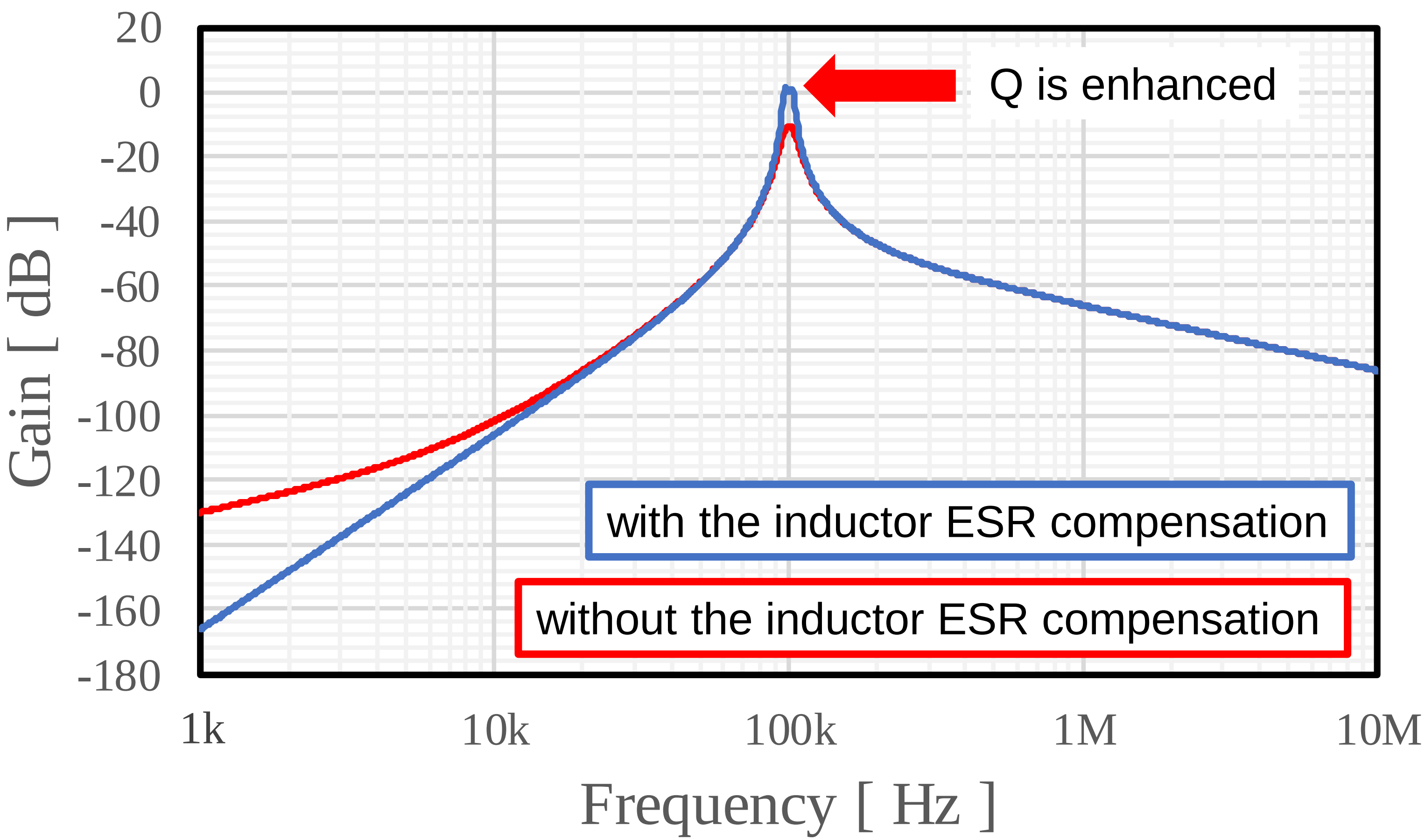


LC analog BPF with proposed inductor ESR compensation

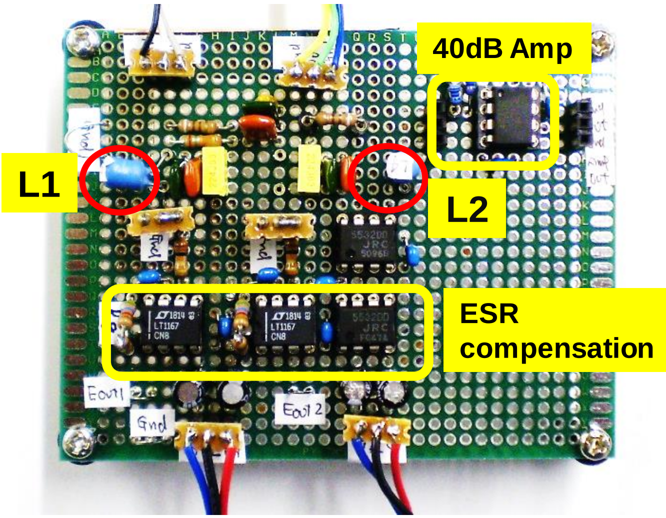
Transfer function of an ideal LC BPF

$$G(s) = \frac{s^3 R_t L^2 C_C}{s^4 R_i R_t L^2 C(2C_C + C) + s^3 L^2 (C + C_C)(R_i + R_t) + s^2 L\{2R_i R_t (C_C + C) + L\} + sL(R_i + R_t) + R_i R_t}$$

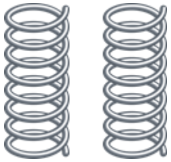
Simulation Verification



Measurement Result of BPF Prototype



LC BPF prototype
with ESR compensation

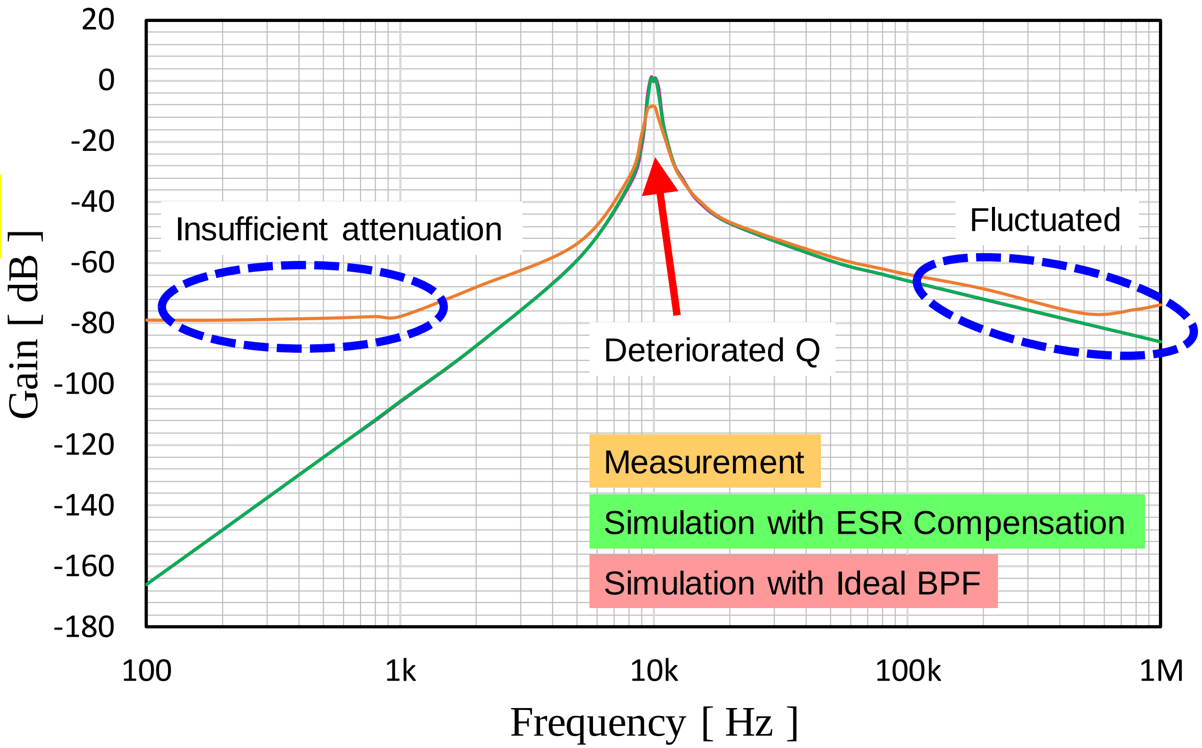


L_1, L_2 are placed in parallel

⇓

Parasitic mutual conductance

Simulation and measurement result
of BPF with ESR compensation,



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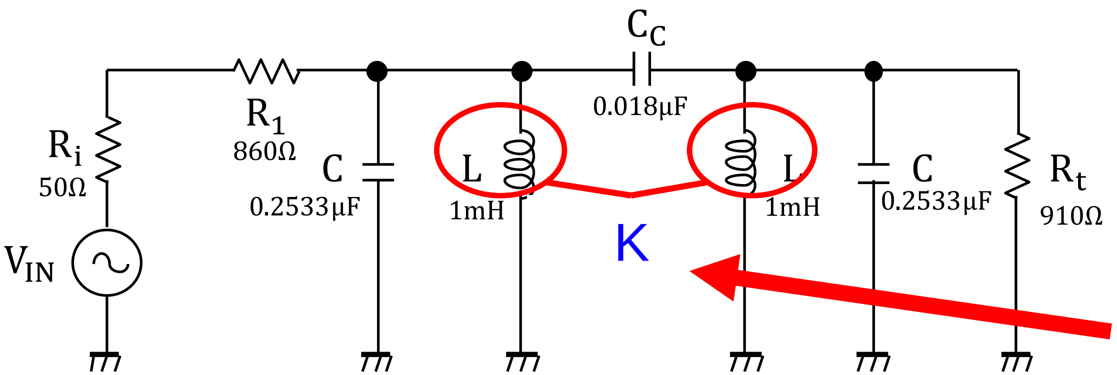
Discrepancies

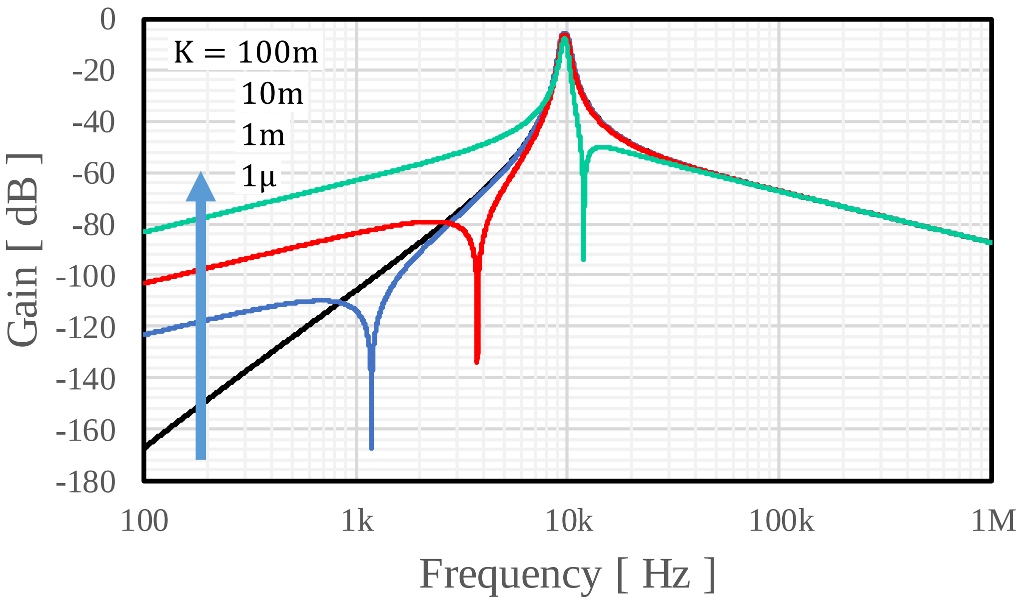
Effect of Coupling Coefficient K

Simulation of mutual inductance effect



Coupling coefficient

Circuit

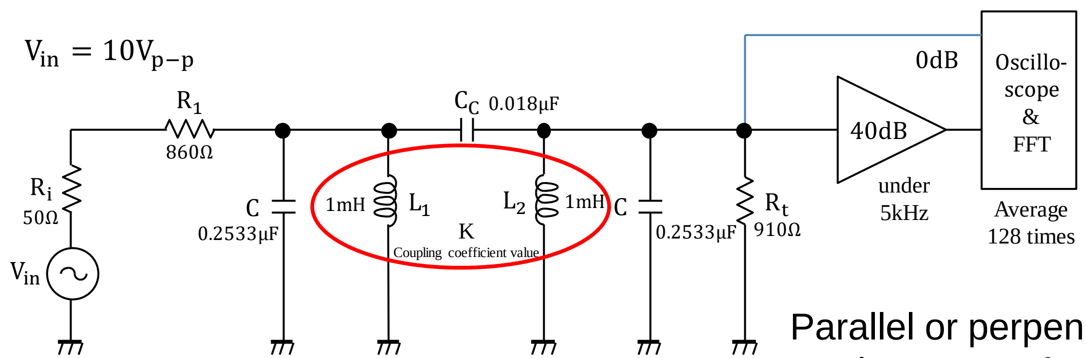


K increases

Stop band attenuation in low frequency side becomes worse.

L_1, L_2 Parallel or Perpendicular Placement

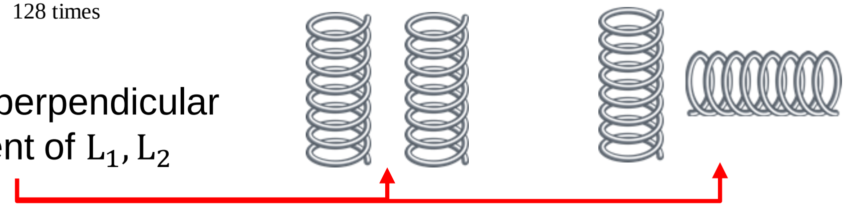
BPF measurement result

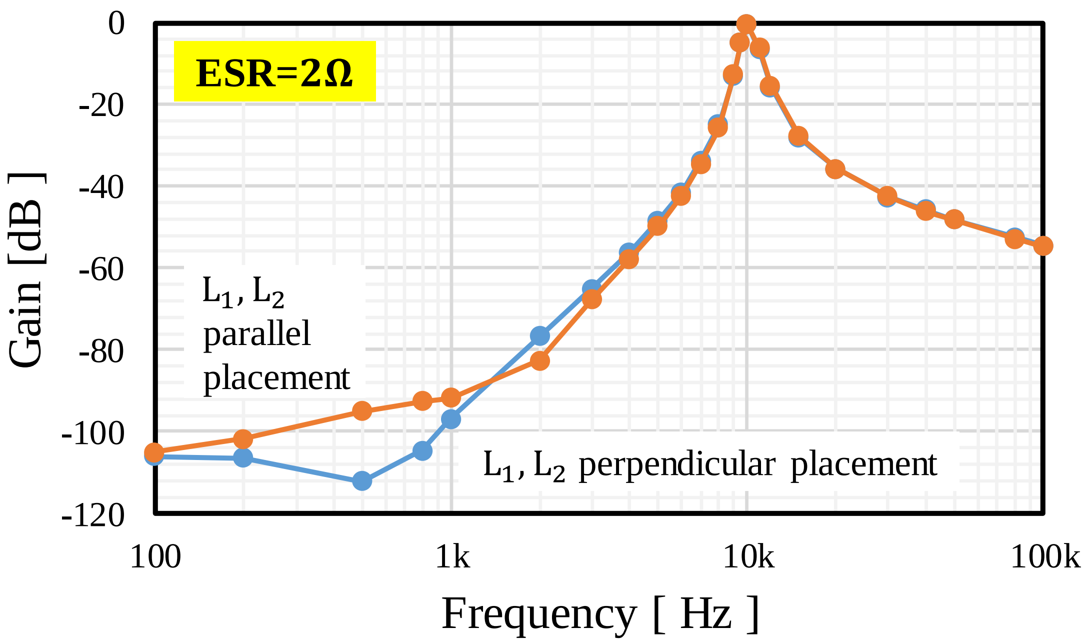


For accurate measurements in stopband,

- Amplifier of 40 dB gain under 5kHz
- 128 times averaging

Parallel or perpendicular placement of L_1, L_2





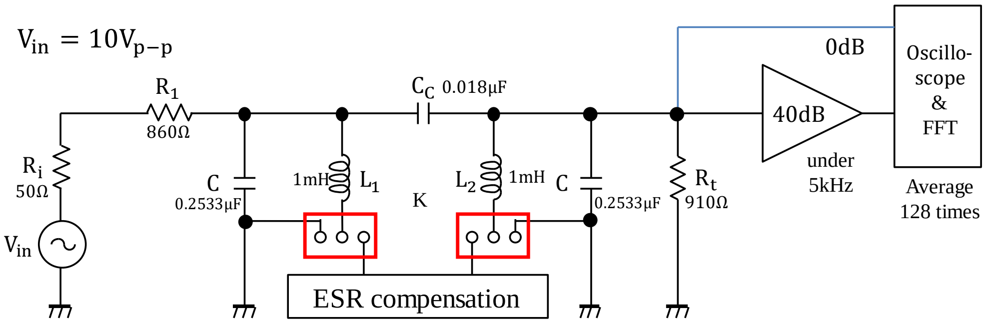
L_1, L_2 are placed in perpendicular

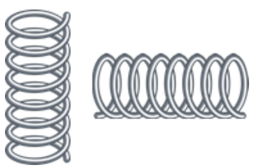
Mutual inductance reduction

Stop band attenuation

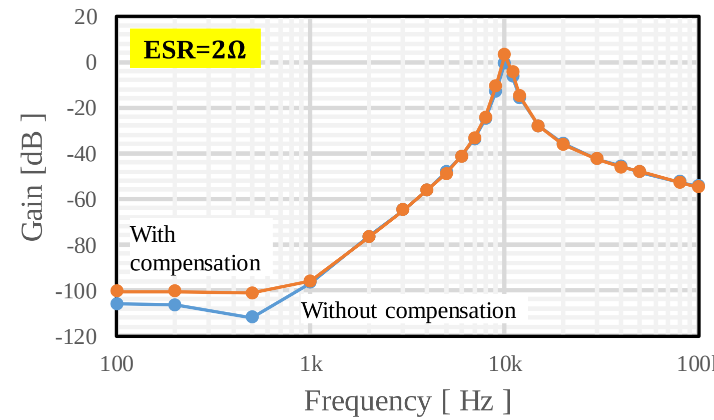
Improved

Measurement of 2^{nd} BPF Prototype

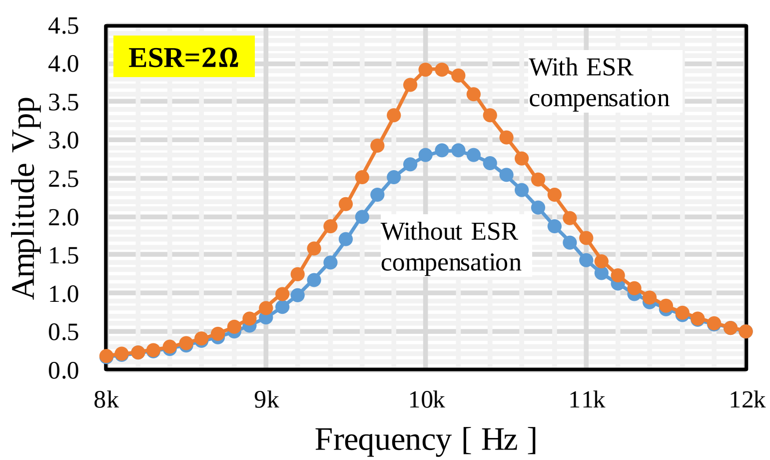




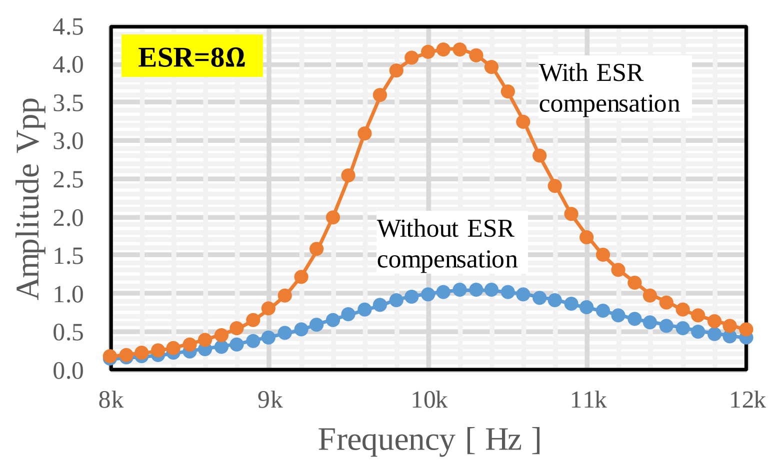
Perpendicular placement of L_1, L_2



Measured result with ESR of 2Ω



Enlarged with ESR of 2Ω



Enlarged with ESR of 8Ω

Q is enhanced

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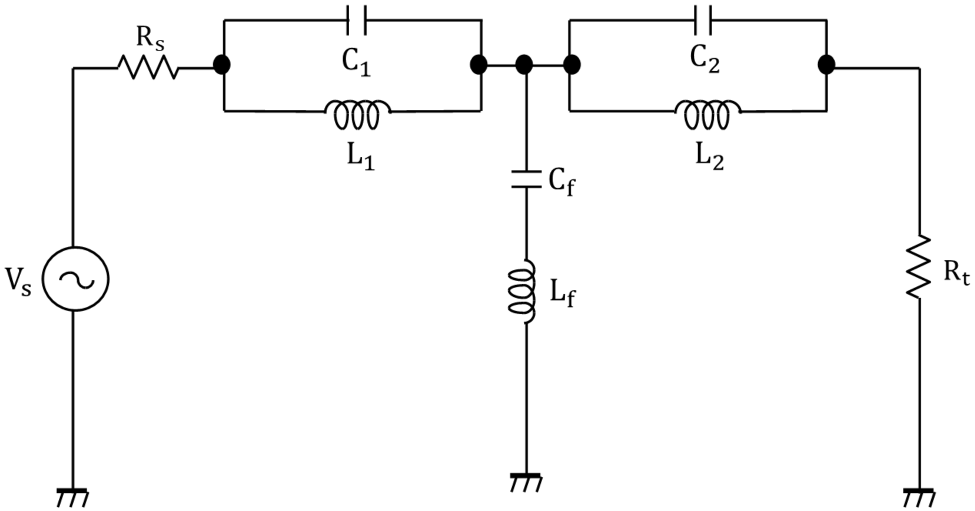
Application to LC BEF

BEF for THD measurement



LC BEF circuit

Low-distortion sinusoidal signal is applied to DUT

⇩

Fundamental component of its output is removed by BEF

⇩

Harmonic components are amplified and measured

⇩

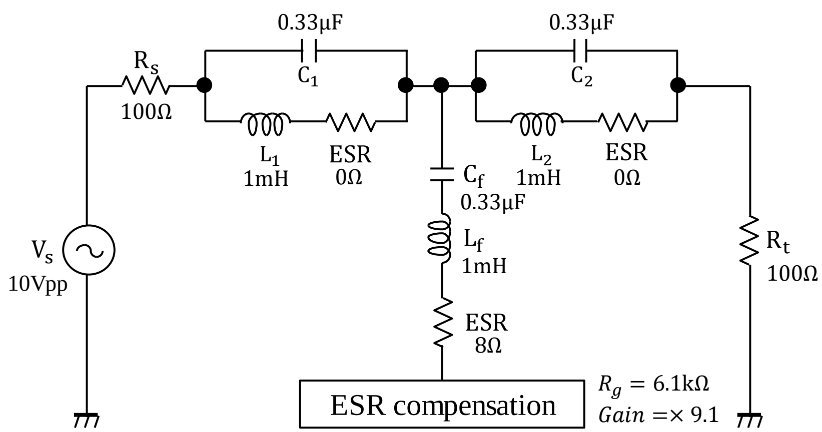
High dynamic range THD measurement

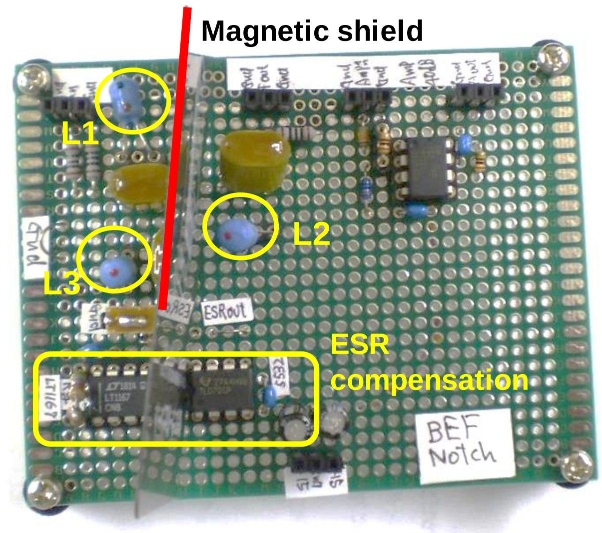
Transfer function

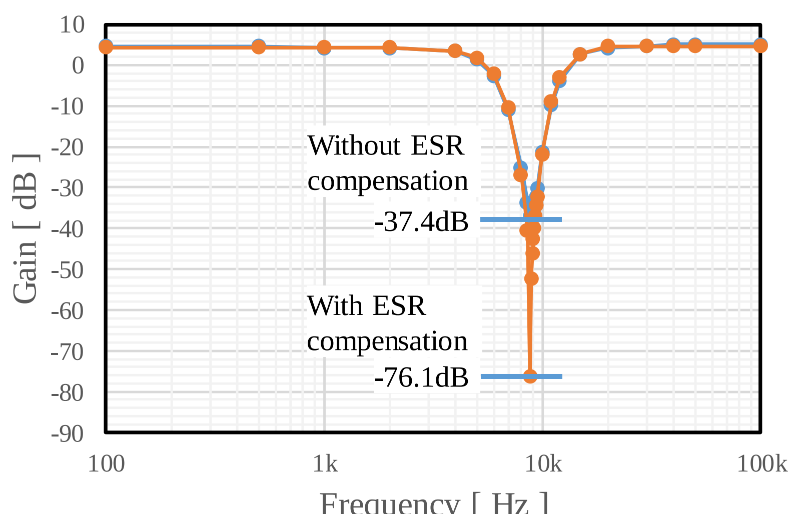
$$G(s) = \frac{(s^2L_1C_1+1)(s^2L_fC_f+1)(s^2R_tL_2C_2+R_t)}{(s^2R_sL_1C_1+sL_1+R_s)\{(s^2L_fC_f+1)(s^2L_2C_2+1)+sC_f(s^2R_tL_2C_2+sL_2+R_t)\}+(s^2L_1C_1+1)(s^2L_fC_f+1)(s^2R_tL_2C_2+sL_2+R_t)}$$

BEF Prototype with Inductor ESR Compensation

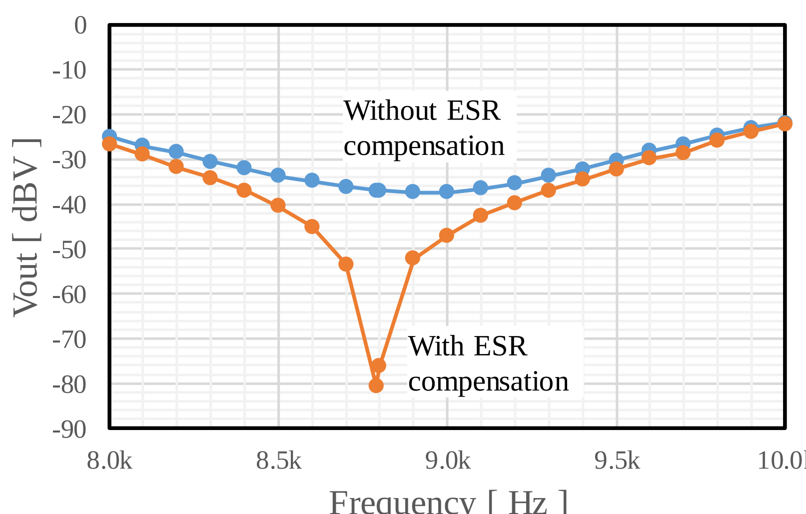
BEF with inductor ESR compensation







Measured result



Enlarged

Notch ⇨ sharper

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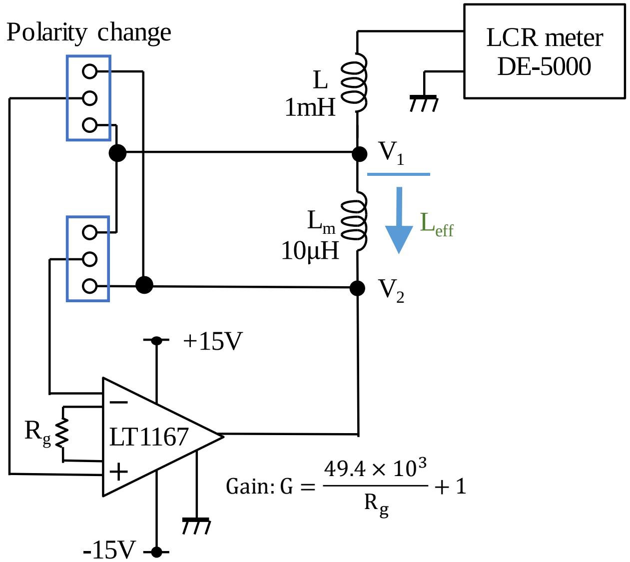
Application to Variable Inductor Realization



Circuit

$V_2 = G(V_2 - V_1)$, $j\omega L_m I = V_1 - V_2 = V_1/(1 - G)$

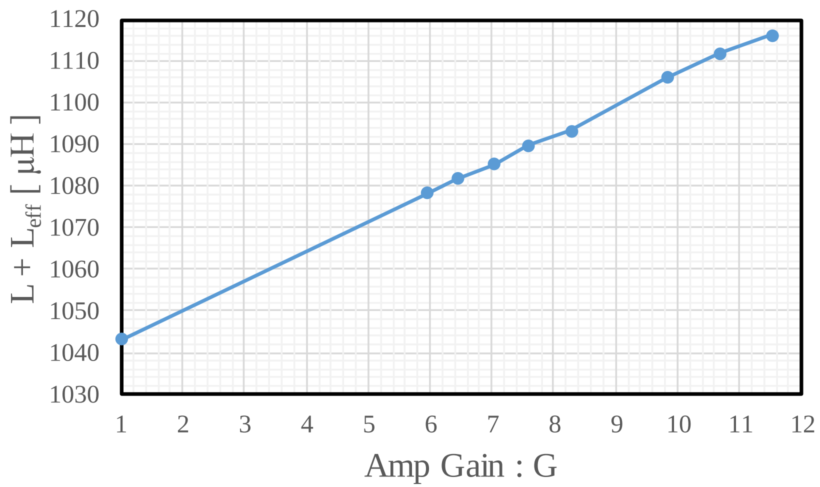
Effective inductor from node V_1:

$$L_{eff} = V_1/(j\omega I) = (1 - G)L_m$$

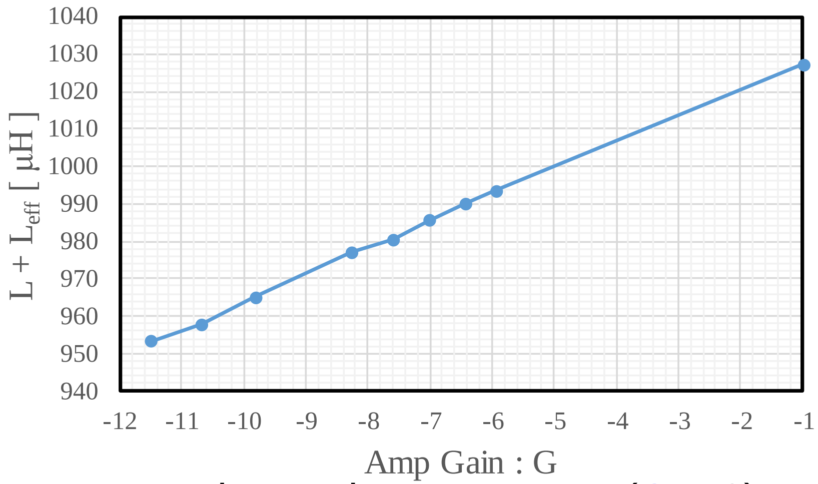
G can be positive or negative by polarity switch

Total inductor $L_{total} = L_{eff} + L$

Measured results with polarity switch change



Inductor increase case (G > 0)



Inductor decrease case (G < 0)

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Conclusion

For low-cost analog/mixed-signal test systems

- Analog LC BPF and BEF
  - Inductor ESR compensation for high Q
  - Variable center frequency
  - Parasitic mutual inductance effects
    - ⇨ Placement of inductors
- Verification with circuit simulation and experiments

Thank you for listening !