Lecture #8 : Tolerance analysis

1. **Importance of tolerance analysis**

2. **Fundamentals of tolerance**
   - o Tolerance and normal distribution
   - o 6σ , Cp, and Cpk
   - o Yield rate and DPU
   - o Poisson distribution

3. **Approach to 6σ design and production**

4. **An example : Tunable filter design**
   - o Description of the tunable filter design
   - o Monte-Carlo analysis

5. **Appendix: Table of normal probability function**

1. Importance of tolerance analysis

- **Tolerance analysis is not important for a prototype design in the Laboratory but, it is very important for a product in the massive production line.**

- **The existence of a product in massive production line depends mainly on the yield rate of the product**

- **Yield rate of a product is mostly determined by the tolerance of all the parts.**

- **The tool of the tolerance analysis in the simulation stage of design is "Monte Carlo".**

- **In some circuit designs, the performance are mainly limitedby the tolerance. The designer must do the tolerance analysis first.**

The following example, a tunable filter design, illustrates the first priority of the tolerance analysis.

2. Fundamentals of tolerance

- **Plot of relative number of resistors versus value of resistor**

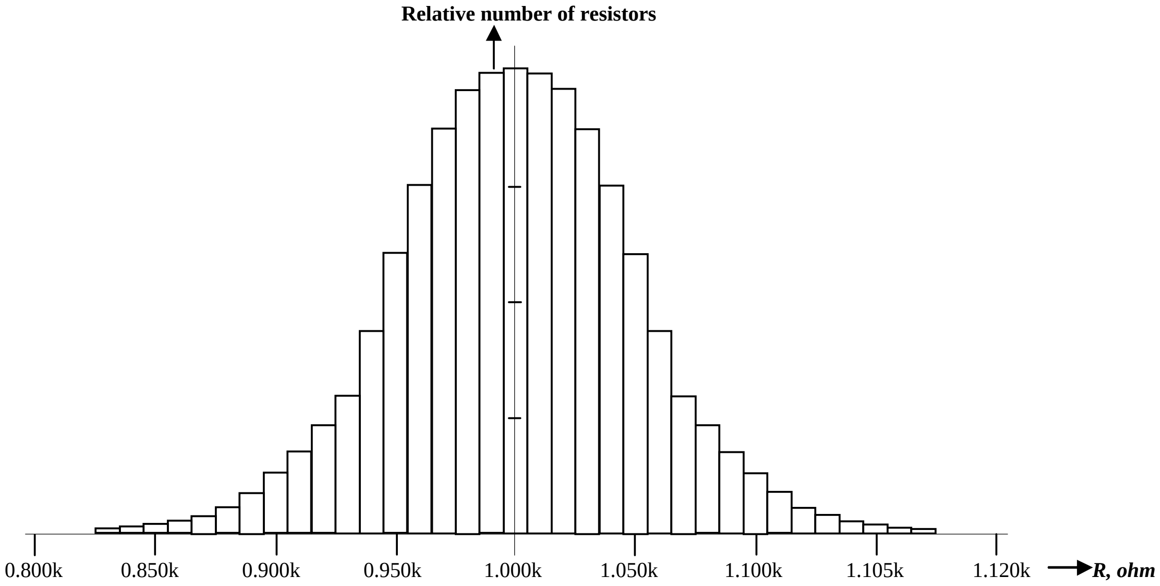


Figure 8.1 Histogram of relative number of resistors versus the value of resistor

o Gaussian probability function

- * **Sample value :** R_i ,

- * **Average value :** $m = 1000$ ohms ,

- * **Relative tolerance :** $Tol_{\text{Re}\,lative} = \dfrac{\sqrt{\sum_i \Delta R_i^{\,2}}}{m} = \dfrac{s}{m} = 5\%$,

- * **Varianceor standard deviation** $s = \sqrt{\sum_i \Delta R_i^{\,2}}$ ohms .

- * **Gaussiondistribution :**

$$f(z) = \int_0^z r(x)dx = \int_0^z \frac{e^{-\frac{x^2}{2s^2}}}{\sqrt{2p}}dx$$

where

$$z = \frac{R-m}{s}$$

$$r(x) = \frac{e^{-\frac{x^2}{2s^2}}}{\sqrt{2p}}$$

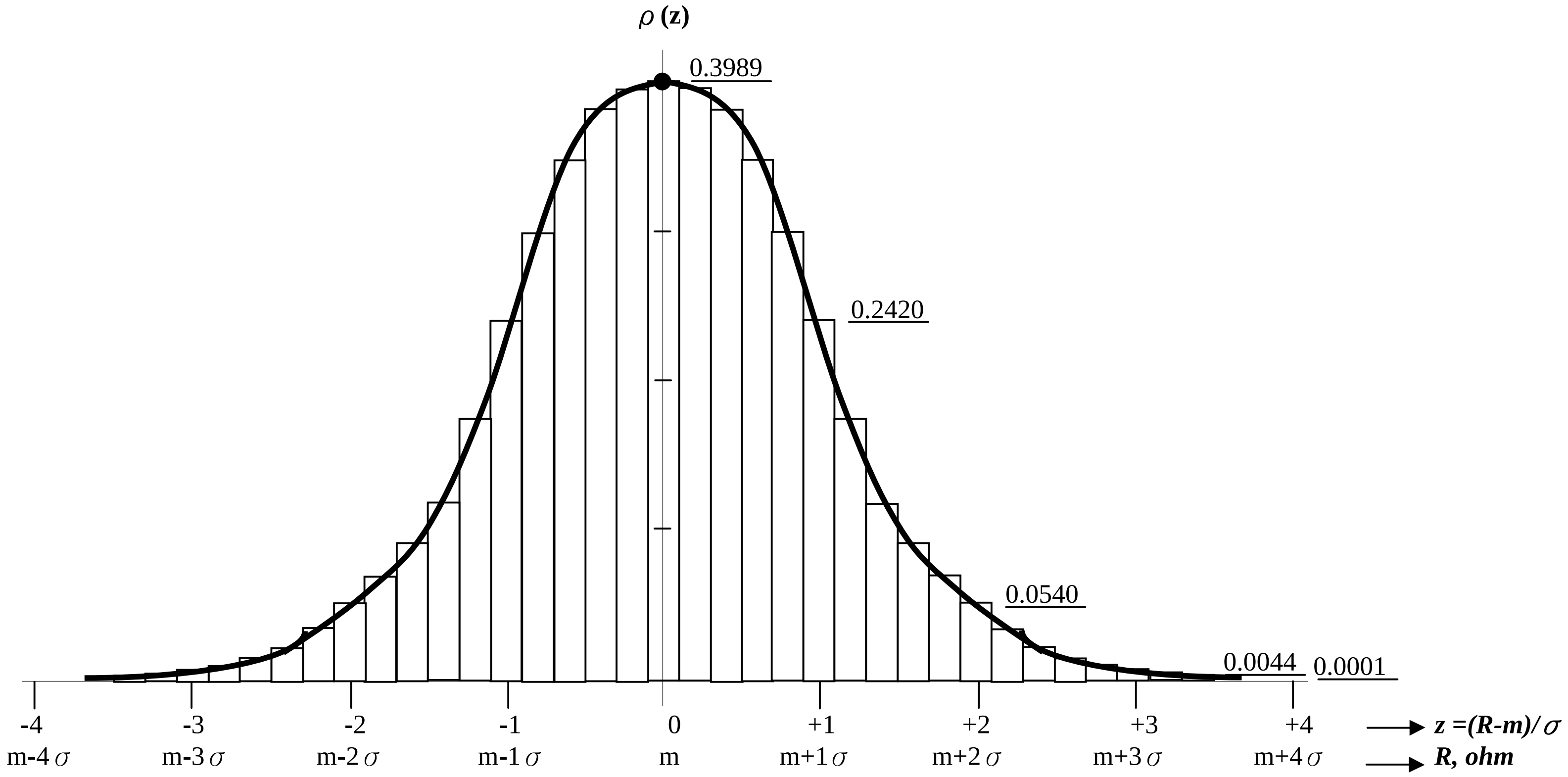


Figure 8.2 Distribution of the random variable, R, is a Normal probability function or a Gaussian distribution

o Tolerance and normal distribution

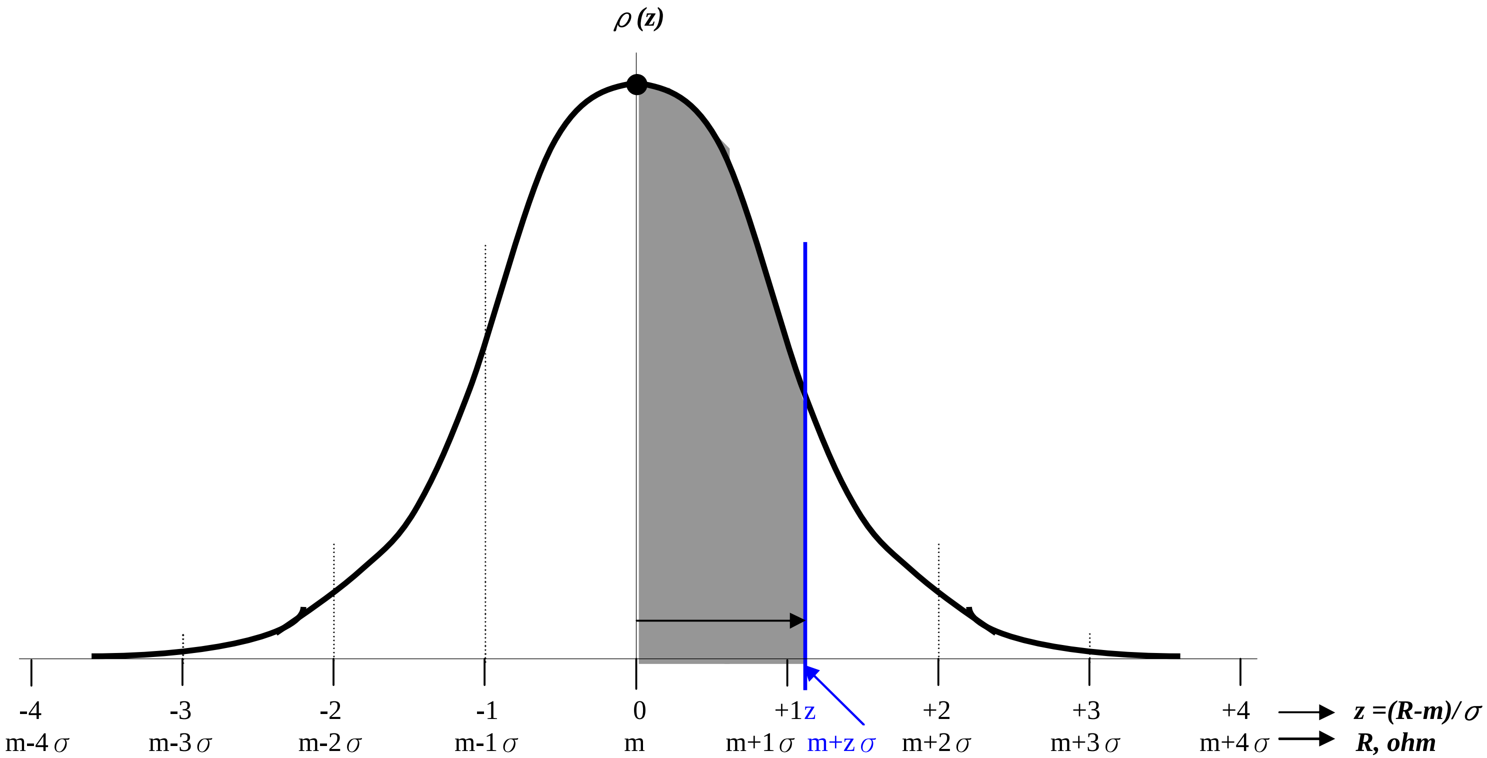


Figure 8.3 Integral of $\rho(z)$ from 0 to z or from m to $m+z\sigma$.

o Six sigma and 100% yield rate

Gaussian distribution :

$$f(z) = \int_0^z \frac{e^{-\frac{(x-m)^2}{2s^2}}}{\sqrt{2ps^2}} dx$$

where m **= average of the variable x ;**

σ **= square root of the variable x.**

Normal probability function is a Gaussian distribution function when : m = 0 , and σ = 1 .

$$f(z) = \int_0^z \frac{e^{-\frac{x^2}{2}}}{\sqrt{2p}} dx = \frac{1}{2} erf\left(\frac{z}{\sqrt{2}}\right)$$

$$erf(x) = \frac{2}{\sqrt{p}} \int_0^x e^{-y^2} dy$$

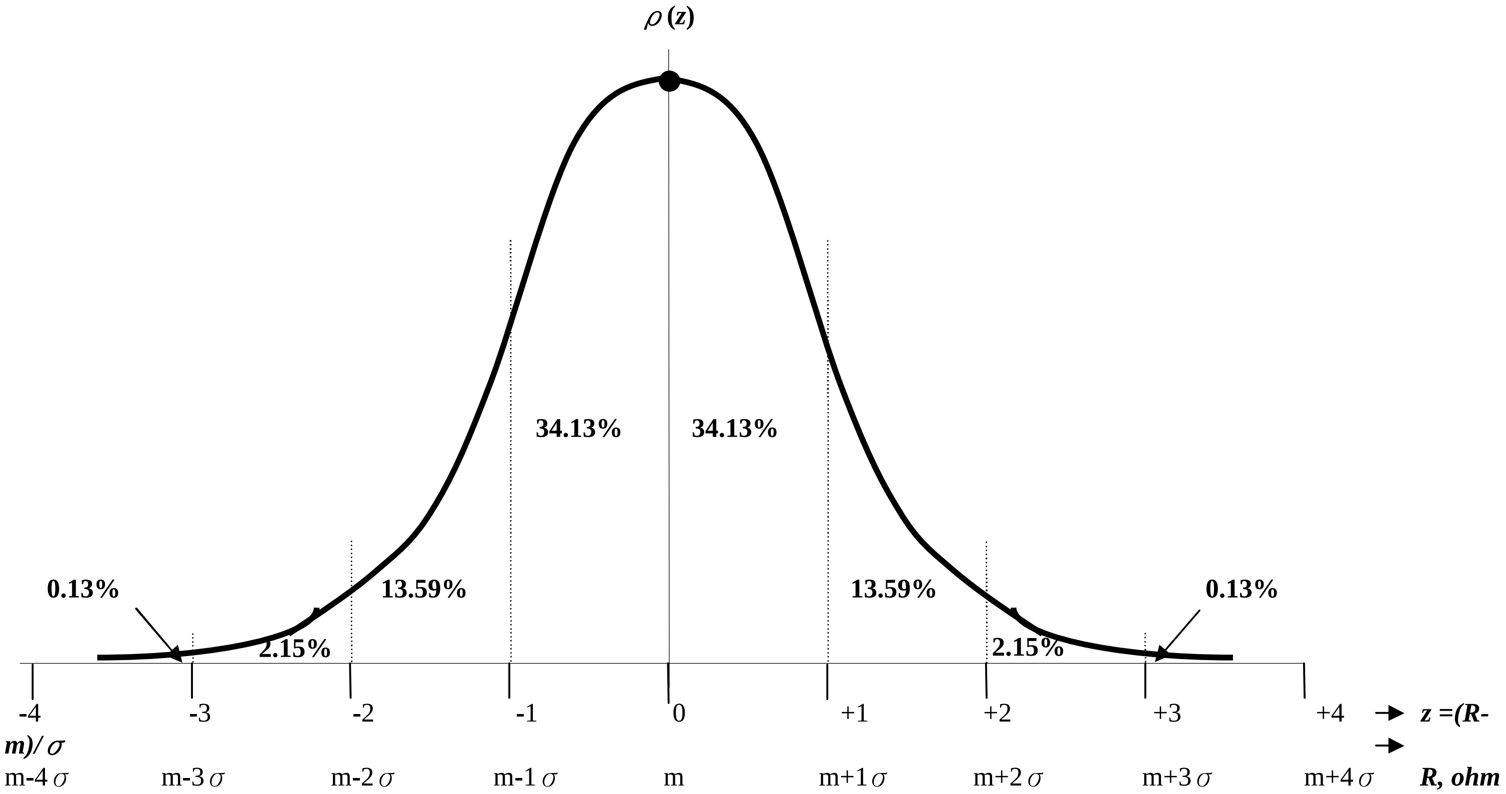


Figure 8.4 At each interval, z, the appearing percentage of arandom variable with a Normal distribution

when the interval is $-1\sigma < z < +1\sigma$, then the area is $f(z) = 68.26\%$,
when the interval is $-2\sigma < z < +2\sigma$, then the area is $f(z) = 95.44\%$,
when the interval is $-3\sigma < z < +3\sigma$, then the area is $f(z) = 99.74\%$,
when the interval is $z < -3\sigma$, and $z > +3\sigma$, then the area is $f(z) = 0.26\%$,

o 6σ, C_p, and C_{pk}

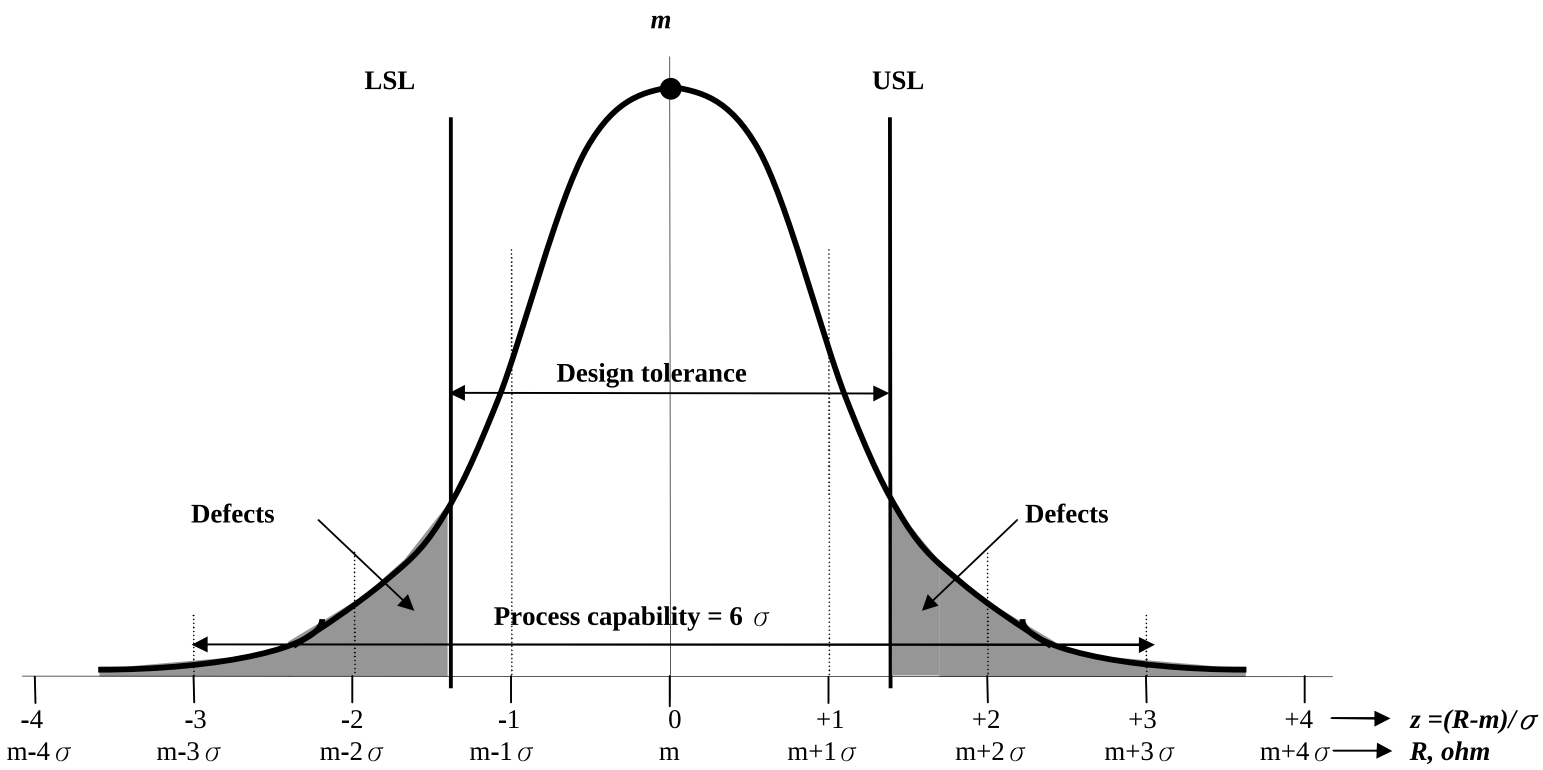


Figure 8.5 The various terminologies of a process with normaldistribution

USL = Upper specification limit, σ ,
LSL = Lower specification limit, σ .

$$Tolerance = USL - LSL$$

$$Defects = 1 - f(z = USL) - f(z = LSL)$$

where **USL = Upper specification limit,** σ **,**
LSL = Lower specification limit, σ **.**

Capability Index, C_p, is defined as

$$C_p = \frac{Design\_Tolerance}{\Pr ocess\_Capability} \approx \frac{USL - LSL}{6s}$$

Adjusted Capability Index, C_{pk}, is defined as

$$C_{pk} = C_p(1 - K)$$

where **m = Nominal process mean,** σ **,**
m' = Actual process mean, σ **.**

$$K = \frac{m - m'}{(USL - LSL)/2}$$

Example #1

$$Defects = 1 - 2f(z = 2s) = 1 - 2 * 47.72\% = 5.56\%$$

$$C_p = \frac{USL - LSL}{6s} = \frac{4s}{6s} = 0.6667 \qquad K = \frac{|m - m'|}{(USL - LSL)/2} = 0$$

$$C_{pk} = C_p(1 - K) = 0.6667(1 - 0) = 0.6667$$

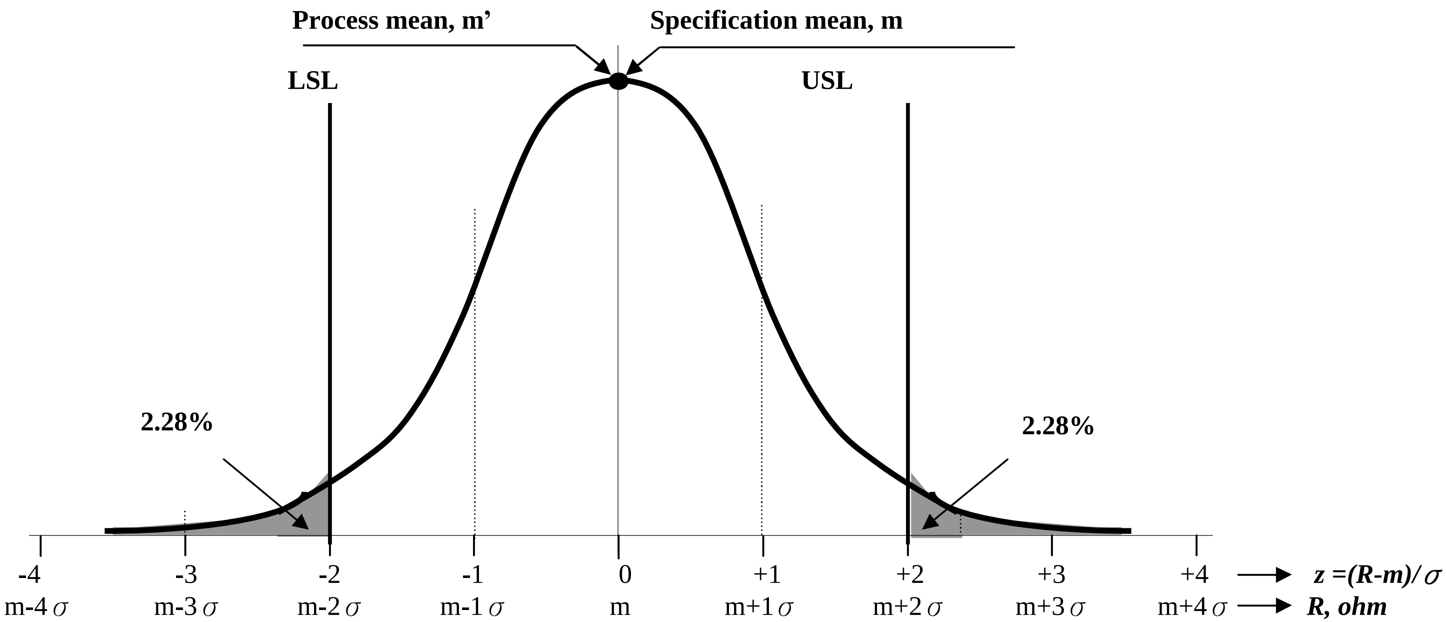


Figure 8.6 A normal distribution with m=10, σ =0.01, USL-LSL=4σ, m'=m .

Example #2

$$Defects = 1 - 2f(z = 3s) = 1 - 2 * 49.87\% = 0.26\%$$

$$C_p = \frac{USL - LSL}{6s} = \frac{6s}{6s} = 1.0000 \qquad K = \frac{|m - m'|}{(USL - LSL)/2} = 0$$

$$C_{pk} = C_p(1 - K) = 1.0000(1 - 0) = 1.0000$$

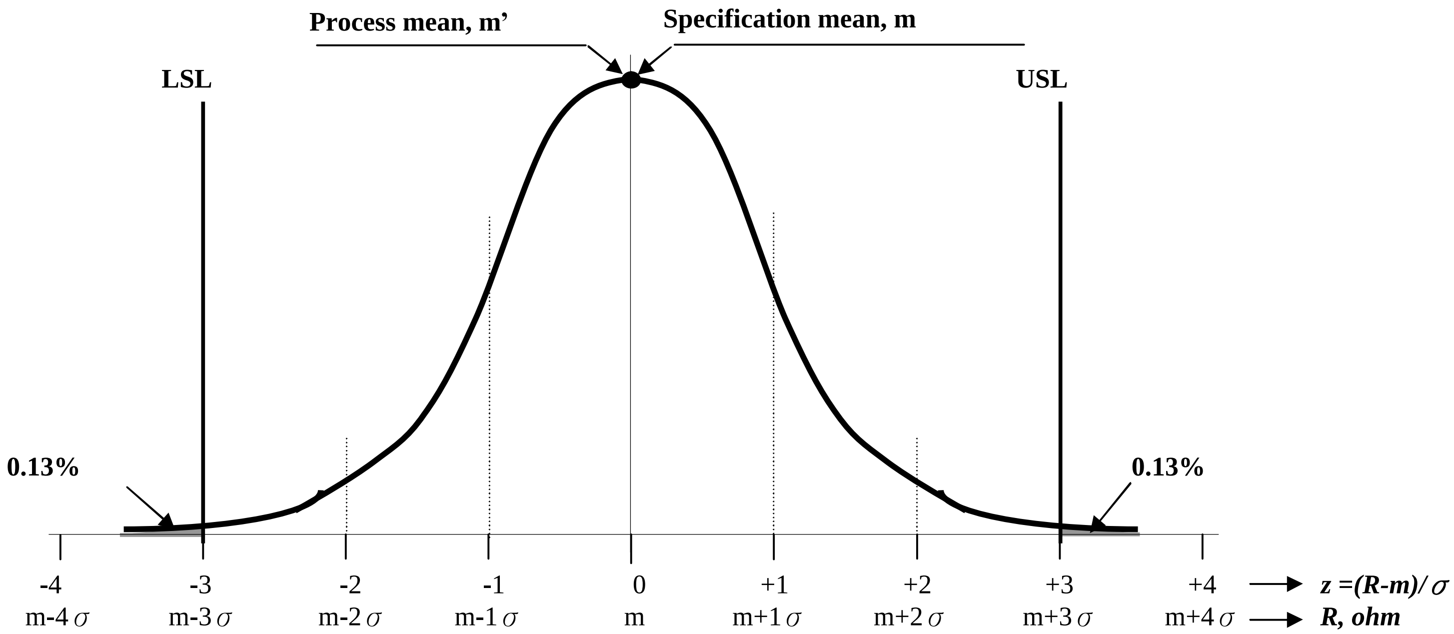


Figure 8.7 A normal distribution with m=10, σ =0.01, USL-LSL=6σ , m'=m .

Example #3

$$Defects = 1 - f(z = 3s) - f(z = -s) = 1 - 34.13\% - 49.87\% = 16\%$$

$$C_p = \frac{USL - LSL}{6s} = \frac{4s}{6s} = 0.6667 \qquad K = \frac{|m - m'|}{(USL - LSL)/2} = \frac{1}{4/2} = 0.5000$$

$$C_{pk} = C_p(1 - K) = 0.6667(1 - 0.5) = 0.3334$$

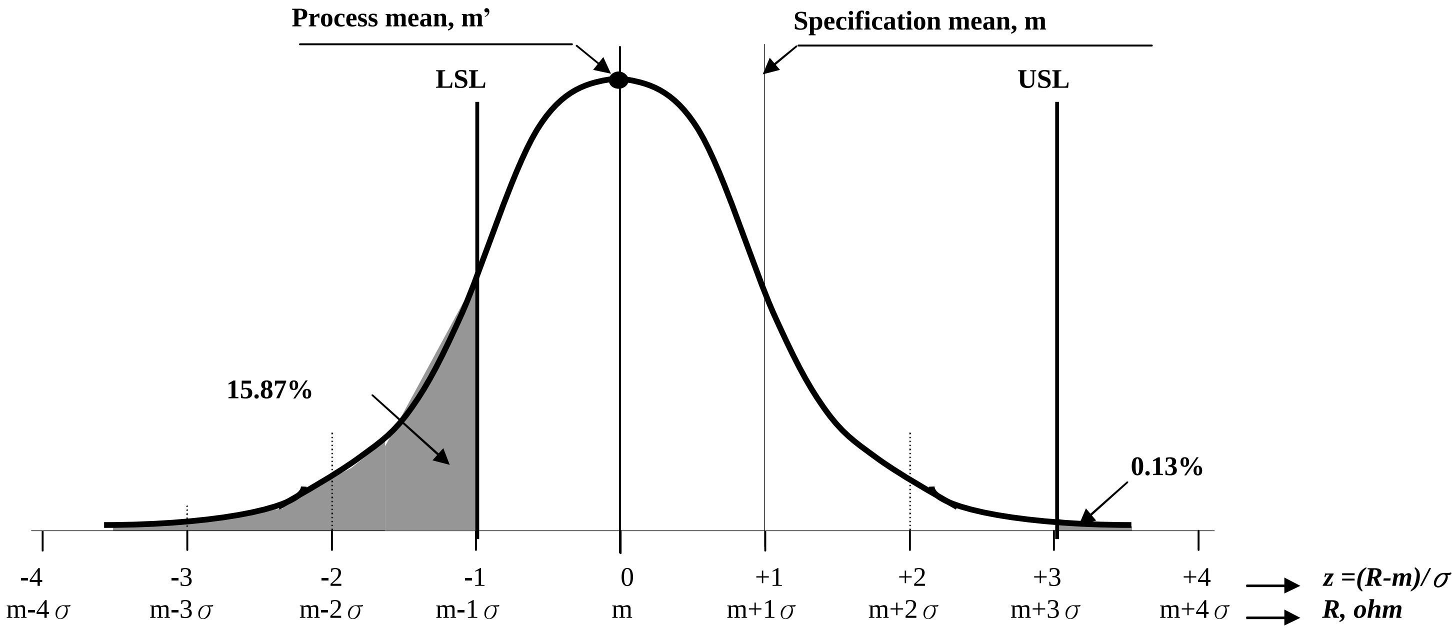


Figure 8.8 A normal distribution with m=10, σ =0.01, USL-LSL=4σ , m'=9.99 .

Example #4

$$Defects = 1 - f(z = 0s) - f(z = -4s) = 1 - 0\% - 50\% = 50\%$$

$$C_p = \frac{USL - LSL}{6s} = \frac{4s}{6s} = 0.6667 \qquad K = \frac{|m - m'|}{(USL - LSL)/2} = \frac{2}{4/2} = 1$$

$$C_{pk} = C_p(1 - K) = 1.0000(1 - 1) = 0$$

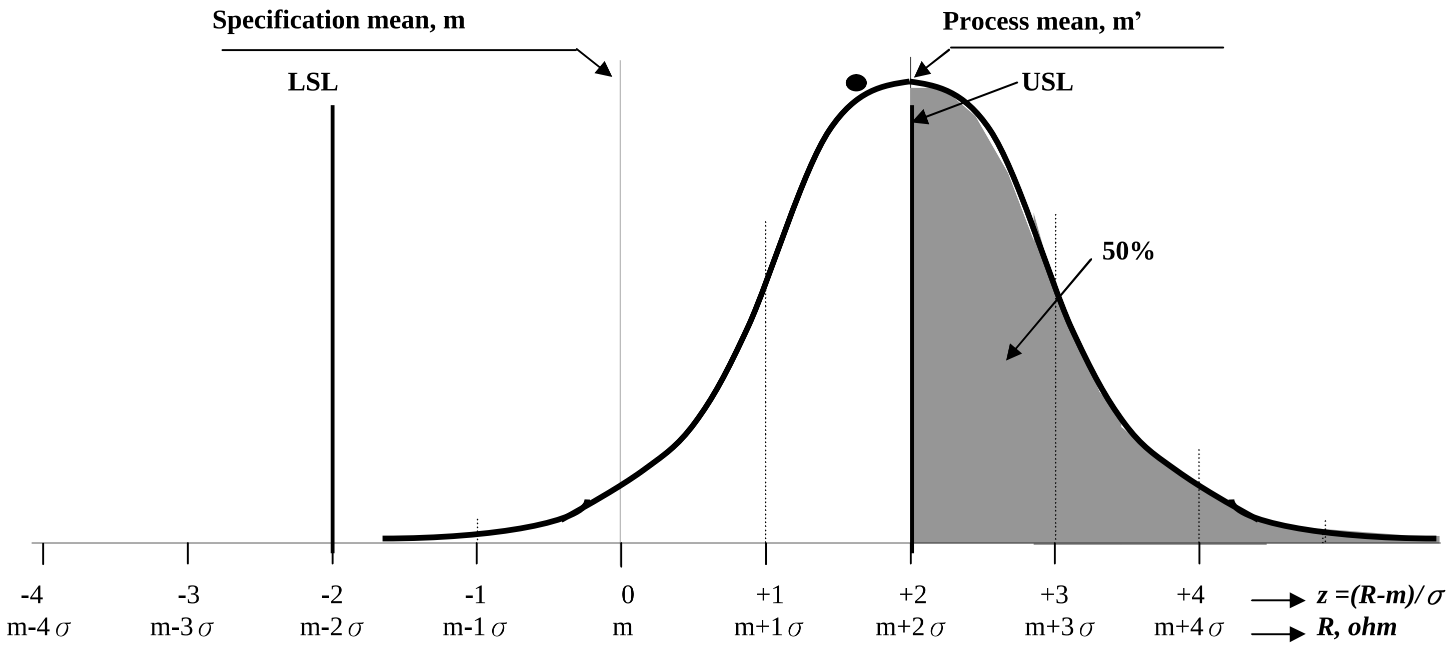


Figure 8.9 A normal distribution with m=10, σ =0.01, USL-LSL=4σ, m'=10.02 .

- **Yield rate andDPU**

$$DPU = \frac{N_d}{N_p}$$

where N_d **= Number of defects found at all acceptance points,**
N_p **= Number of units processed.**

o Poisson distribution

Poisson distribution, the occurrence of random defects in manufactured product can be statistically predicted.

Poisson distribution is a mathematic model to describe the probability distribution of the arrived entities. For instance, in one hour lunch time, say, statistically from 12.00 to 13.00 o'clock, the number of customers getting into a restaurant for lunch. Assuming that the average number of customers is μ, and the random number of arrivals at the same time interval is x, then the probability of the random arrival number, P{x}, is

$$P\{x\} = \frac{m^{x} e^{-m}}{x!}$$

$$P\{0\} = \frac{DPU^{0} e^{-DPU}}{0!} = e^{-DPU}$$

this is the relationship between the defect-free probability and the average DPU. The first time yield, FTY, can be approximated by the formula:

$$FTY = e^{-DPU}$$

And, in general

$$P\{x\} = \frac{DPU^{x} e^{-DPU}}{x!}$$

If a process with N steps, 1,2,3,4….N, and the value of DPU in each step is a, b, c, d, ……n respectively. Then, in terms of the formula, the first time yield, FTY, is e^{-a}, e^{-b}, e^{-c}, e^{-d}……e^{-n} correspondingly. The fist time rolled yield for the process is

$$Defect\_rate_{PPM/part} = PPM/part = \frac{DPU}{Parts\_Count}$$

Regardless of process flow or order, the rolled yield can be calculated from the summation of the DPU values in all the steps.

$$FTY_{rolled} = FTY\{A\} * FTY\{B\} * FTY\{C\} * FTY\{D\} ..... * FTY\{N\}$$

$$FTY_{rolled} = e^{-(a+b+c+d+......+n)}$$

Example :

Rolled yield for a printed circuit board.

Assuming that there are totally 3 steps :

Parts placed, parts soldered, and parts assembly.

a) Part placement = 300 PPM,
it means 300 parts failed in 1million parts.

b) Part assembly defect rate = 800 PPM,
it means 800 assembly-components failed in 1 million parts.

c) Solder defect rate = 200 PPM,
it means 200 connected points failed in 1million parts.

***) On average, there are 2.3 connections for each part.**

Table 8.1 Calculated FTY for a printed circuit board assemblyby 3 process steps

# of parts	Parts placement a	Parts assembly b	Parts soldered c	Total a+b+c	Rolled FTY $e^{-(a+b+c)}$
100	0.030	0.080	0.046	0.156	85.6%
500	0.150	0.400	0.230	0.780	45.8%
1000	0.300	0.800	0.460	1.560	21.0%

- Approach to 6σ design and production

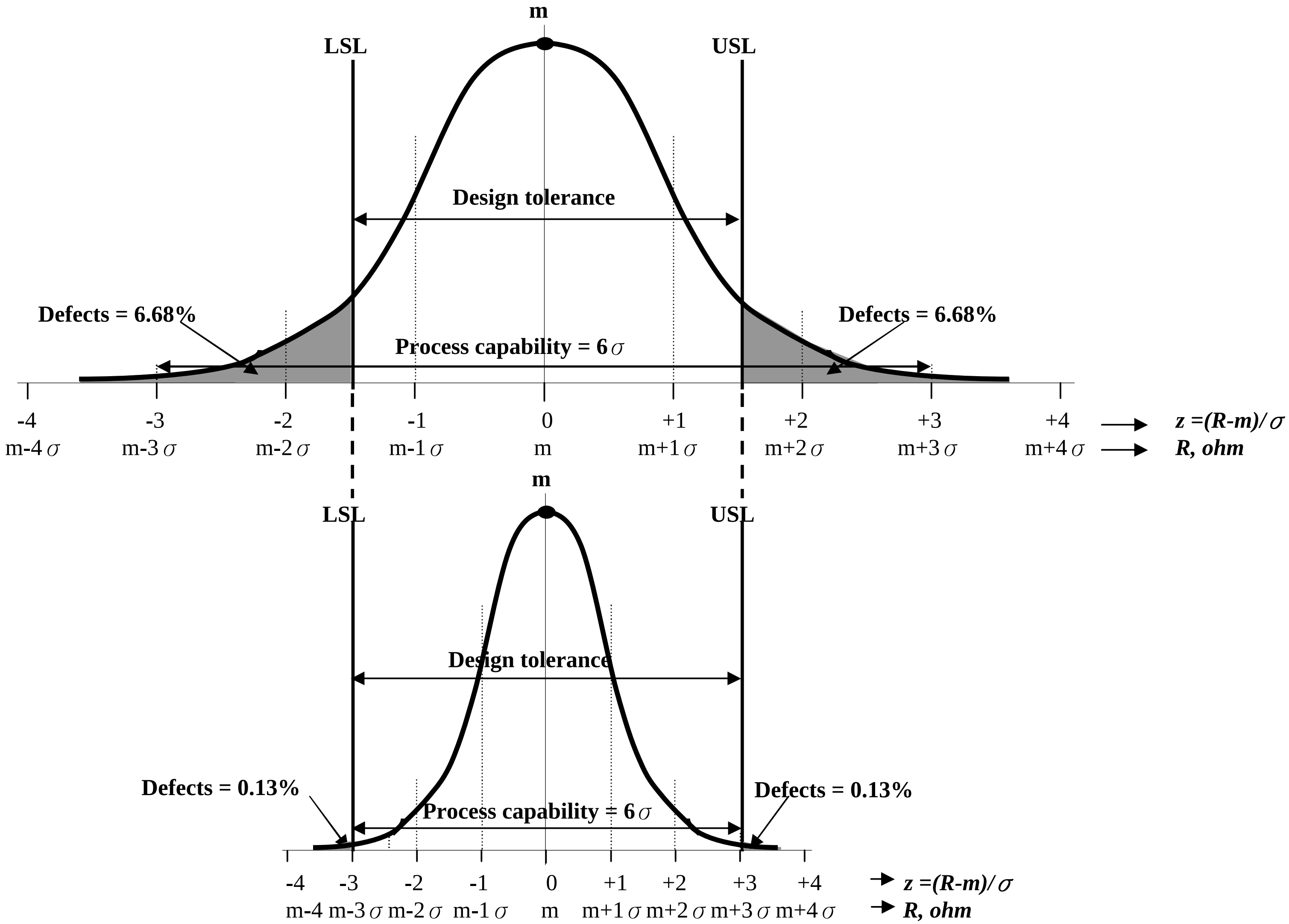


Figure 8.10 Difference of defects when the value of σ is 50% decreased

3. Approach to 6 σ design and production

- **Resistor has highest tolerance in IC design**
  For instance,

$$\left.\frac{\Delta R}{R}\right|_{R=100\ \Omega} \Rightarrow \pm 20\%$$

- **Usually, component with higher values has lower relative tolerance.**

  For instance, with the same processing,

$$\left.\frac{\Delta R}{R}\right|_{R=10\ k\Omega} = \frac{1}{2}\left.\frac{\Delta R}{R}\right|_{R=5\,k\Omega}$$

- **Resistors in parallel**

To build a 5kΩ resistor

by 5kΩ resistor **by 10kΩ resistors**

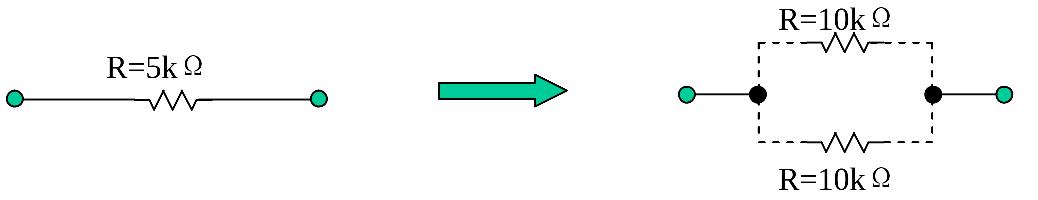


Figure 8.11 A 5 kΩ resistor is replaced by two 10 kΩ resistors in parallel

$$R_{t1} = R \Big|_{R=5\,k\Omega} \qquad R_{t2} = \frac{RR}{R+R} = \frac{R}{2}\Big|_{R=10\,k\Omega}$$

$$\frac{\Delta R_{t1}}{R_{t1}} = \frac{\Delta R}{R}\Big|_{R=5\,k\Omega} \qquad \frac{\Delta R_{t2}}{R_{t2}} = \frac{\Delta R}{R}\Big|_{R=10\,k\Omega}$$

If $$\frac{\Delta R}{R}\Big|_{R=5\,k\Omega} = 2\,\frac{\Delta R}{R}\Big|_{R=10\,k\Omega}$$

Then, $$\frac{\Delta R_{t2}}{R_{t2}} = \frac{1}{2}\,\frac{\Delta R_{t1}}{R_{t1}}$$

o Capacitors in series

To build a 5pF capacitor

by 5pF capacitor **by 10pF capacitors**

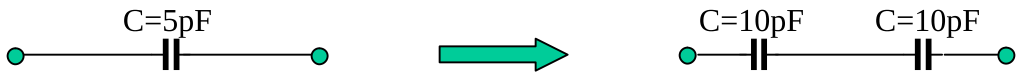


Figure 8.12 A 5 pFcapacitor is replaced by two 10 pFcapacitors in series

$$C_{t1} = C \Big|_{C=5\ pF} \qquad C_{t2} = \frac{CC}{C+C} = \frac{C}{2}\Big|_{C=10\ pF}$$

$$\frac{\Delta C_{t1}}{C_{t1}} = \frac{\Delta C}{C}\Big|_{C=5\ pF} \qquad \frac{\Delta C_{t2}}{C_{t2}} = \frac{\Delta C}{C}\Big|_{C=10\ pF}$$

If

$$\frac{\Delta C}{C}\Big|_{C=5\ pF} = 2\,\frac{\Delta C}{C}\Big|_{C=10\ pF}$$

Then,

$$\frac{\Delta C_{t2}}{C_{t2}} = \frac{1}{2}\,\frac{\Delta C_{t1}}{C_{t1}}$$

o Inductors in parallel

To build a 5nH inductortor

by 5nH inductortor **by 10nH inductors**

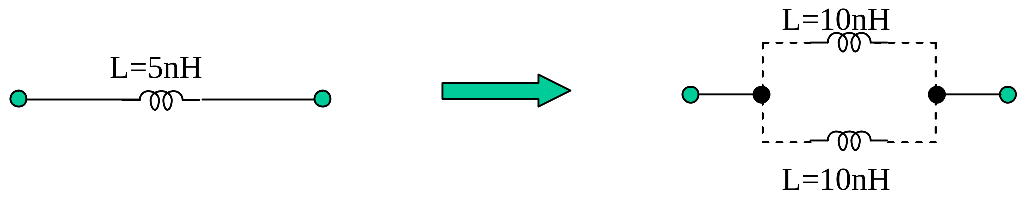


Figure 8.13 A 5 nHinductor is replaced by two 10 nHinductors in series

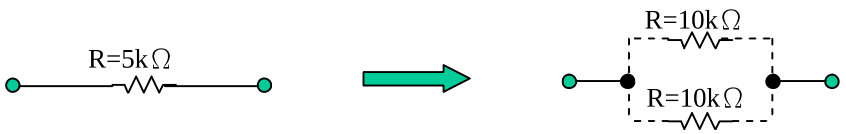
$$L_{t1} = L\Big|_{L=5\,nH} \qquad L_{t2} = \frac{LL}{L+L} = \frac{L}{2}\Big|_{L=10\,nH}$$

$$\frac{\Delta L_{t1}}{L_{t1}} = \frac{\Delta L}{L}\Big|_{L=5\,nH} \qquad \frac{\Delta L_{t2}}{L_{t2}} = \frac{\Delta L}{L}\Big|_{L=10\,nH}$$

If $$\frac{\Delta L}{L}\Big|_{L=5\,nH} = 2\,\frac{\Delta L}{L}\Big|_{L=10\,nH}$$

Then, $$\frac{\Delta L_{t2}}{L_{t2}} = \frac{1}{2}\,\frac{\Delta L_{t1}}{L_{t1}}$$

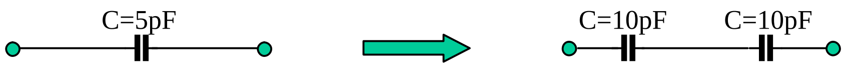
Usually it does not reduce the tolerance by the way of inductors in parallel because it is too expensive !



m = 5kΩ
σ **= 400Ω = 8% of m**

m = 10 kΩ**/2 = 5** kΩ
σ **= 200Ω = 4% of m**

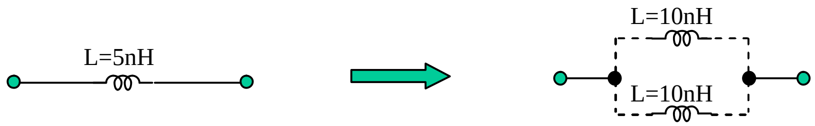
(a) A 5 kΩ resistor is replaced by two 10 kΩ resistors in parallel



m = 5pF
σ **= 0.4 pF= 8% of m**

m = 10 pF**/2 = 5** pF
σ **= 0.2 pF= 4% of m**

(b) A 5 pFcapacitor is replaced by two 10 pFcapacitors in series



m = 5nH
σ **= 0.4 nH= 8% of m**

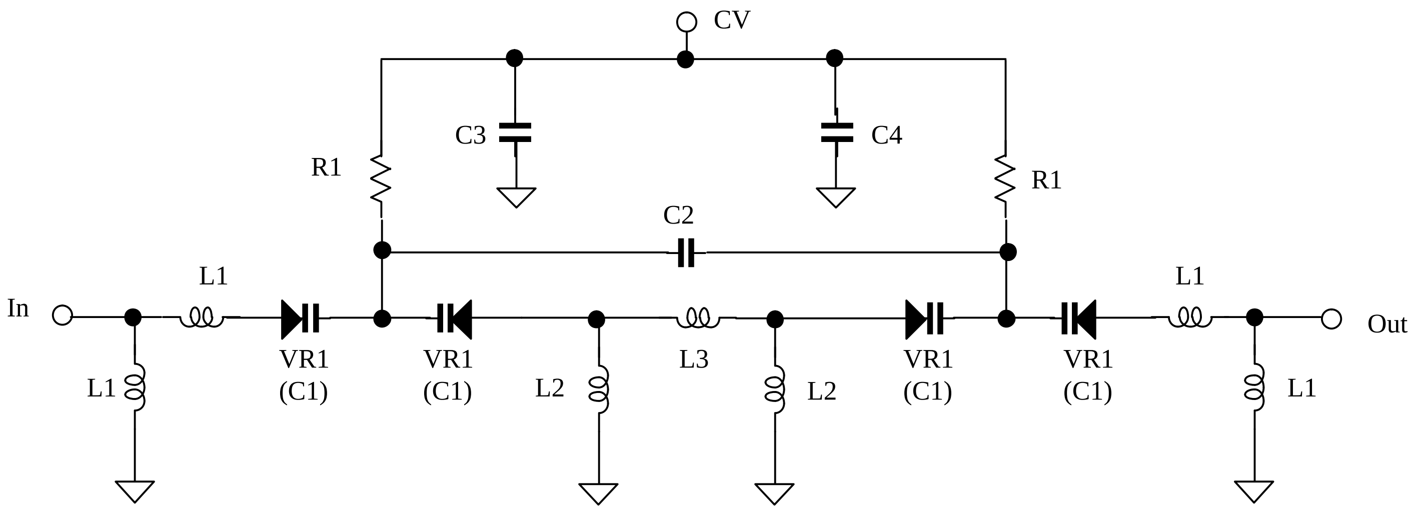
m = 10 nH**/2 = 5** nH
σ **= 0.2 nH= 4% of m**

(c) A 5 nHinductor is replaced by two 10 nHinductors in series

Figure 8.14 Variation of σ in the various replacements

4. An example : Tunable filter design

o Schematic of a tunable filter



L1 : Inductor 4.5 nH// 27 kΩ // 0.2 pF
L2 : Inductor 8.8 nH// 27 kΩ // 0.2 pF
L3 : Inductor 40.5 nH// 27 kΩ // 0.2 pF
C1 : Capacitance of varactor13.75 pFwhen CV=5v

C2 : Capacitor 2.4 pF
C3 : Capacitor 100 pF
C4 : Capacitor 10000 pF

R1 : Resistor 20 kΩ
CV : 5 v

Figure 8.15 Schematic of a *UHF* tunable filter

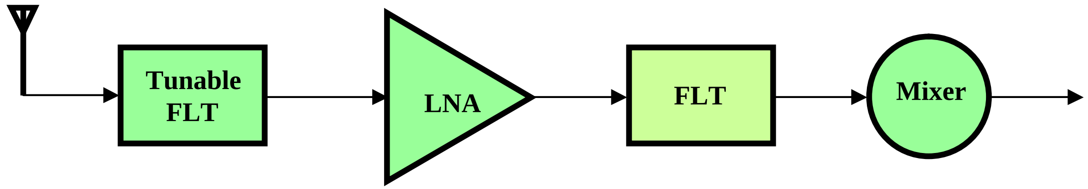
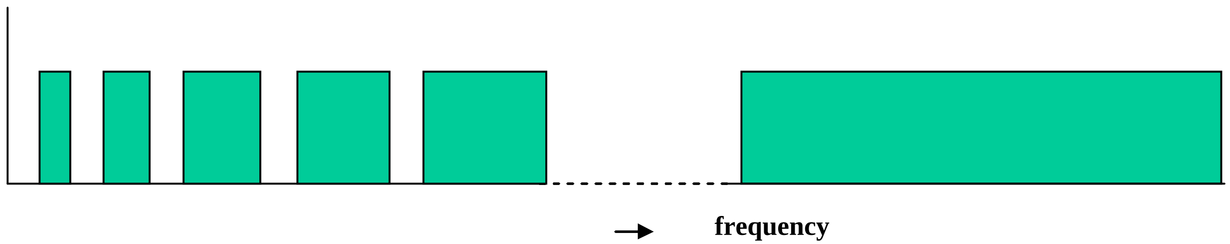
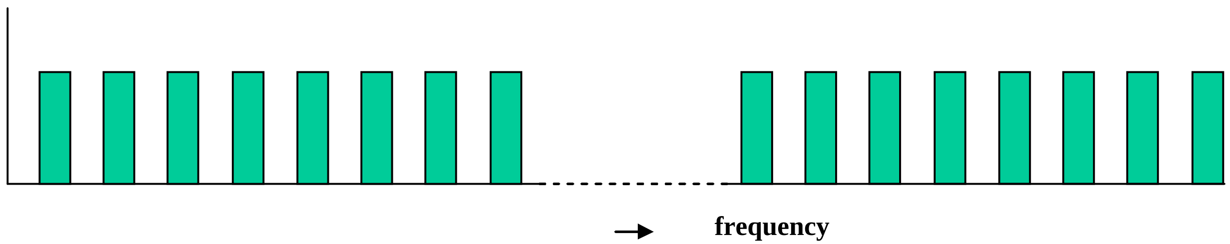


Figure 8.15a A tunable filter is added in the front end of the receiver for better selectivity



(a) Popular cases : Bandwidth is changed as the frequency response is moved



(b) Ideal cases : Bandwidth is kept unchanged as the frequency response is moved

Figure 8.15b Frequency response of a tunable filter moved from low end to high end as the control voltage is increased

o Main coupling : Inductive coupling

- *** An improper coupling unable a tunable filter tuned over a wide frequency tuning range .**
- *** In the case of capacitor coupling,**

$$Q = \omega_o/(BW) = 1/(2RC\omega_o)$$

$$BW = 2RC\omega_o^2$$

$$\partial(BW)/\partial(\omega_o) = 4RC\omega_o$$

- *** In the case of inductor coupling,**

$$Q = w_o/(BW) = Lw_o/(2R)$$

$$BW = 2R/L$$

$$\partial(BW)/\partial(\omega o) = 0$$

where	**Q**	**= Quality factor of filter ;**
	ω_o	**= Tuned central frequency ;**
	BW	**= Bandwidth @** ω_o**;**
	L	**= Inductance of coupling inductor ;**
	R	**= Equivalent resonant resistance of tank circuit @** ω_o**.**

From the above expressions , it is concluded that

1) **In the case of inductor-coupling, the bandwidth of the filter is a constant or independent of the tuning frequency, while**
2) **In the case of capacitor-coupling, the bandwidth of the filter is a function or dependent of the tuning frequency. It is increased as the tuning frequency is increased.**

Consequently,

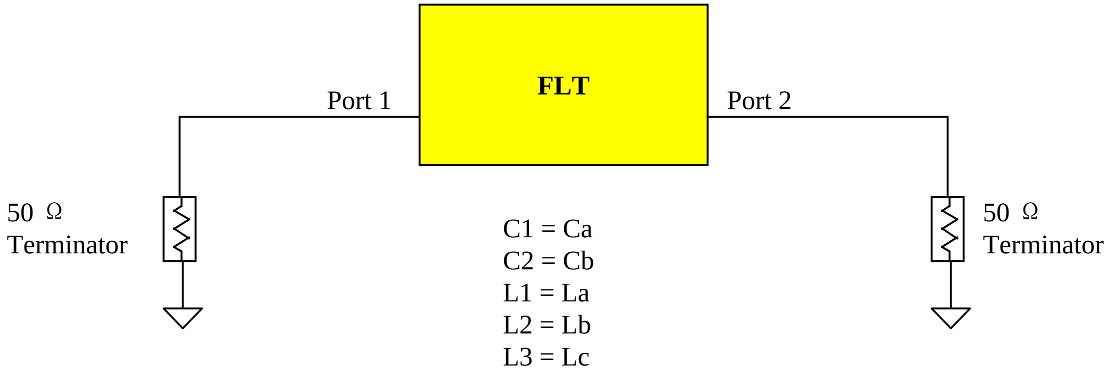
The bandwidth could be kept in an almost constant for a wide tuning frequency range if the coupling element is only an inductor.

It is therefore decided to use an inductor as the primary coupling element between the 2 tank circuits, which is L3 as shown above.

o Second coupling : Capacitive coupling

* **The capacitor, C2, is the second coupling component betweenthe two tank circuits;**
* **It forms a “zero” at the imaginary frequency;**
* **This “zero” traces the central frequency,** ω_o**, over a wide frequency tuning range.**

o Monte Carlo Analysis



Equation Ca = RandvarGaussian, 13.75 pF ±5%
Equation Cb= RandvarGaussian, 2.4 pF ± 5%
Equation La = RandvarGaussian, 4.5 nH ± 7%
Equation Lb = RandvarGaussian, 8.8 nH ± 7%
Equation Lc= RandvarGaussian, 40.5 nH ± 7%

Figure 8.16 Simulation page for Monte-Carlo analysis
(Strictly speaking, it is not a Gaussian but a normal distribution here.)

Figure 7.15 Simulation page for Monte-Carlo analysis
(Strictly speaking, it is not a Gaussian but a normal distribution here.)

* **Frequency response without tolerance**

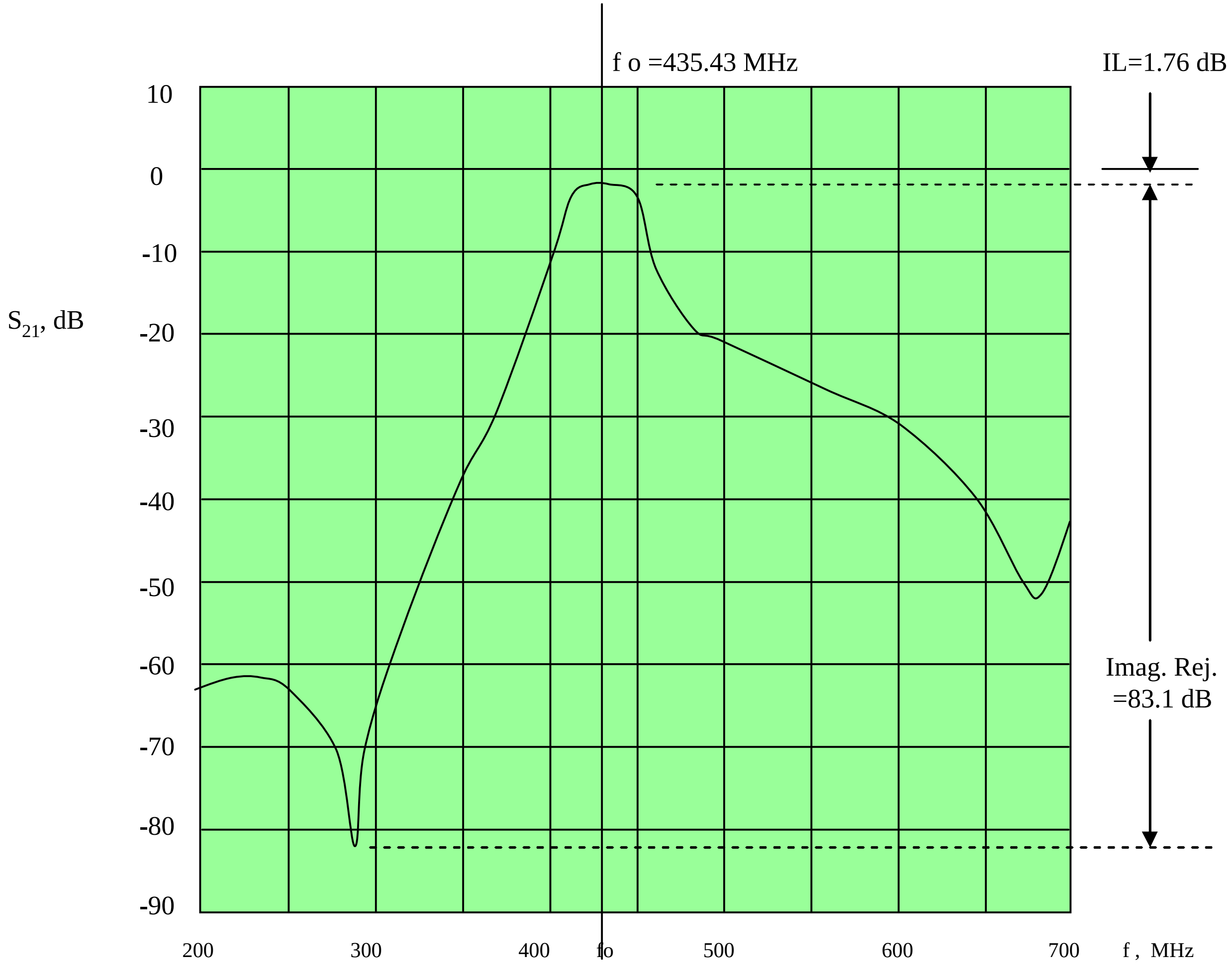


Figure 8.17 Typical frequency response of tunable filter without tolerance

*** Case #3 : Bandwidth is too narrow**

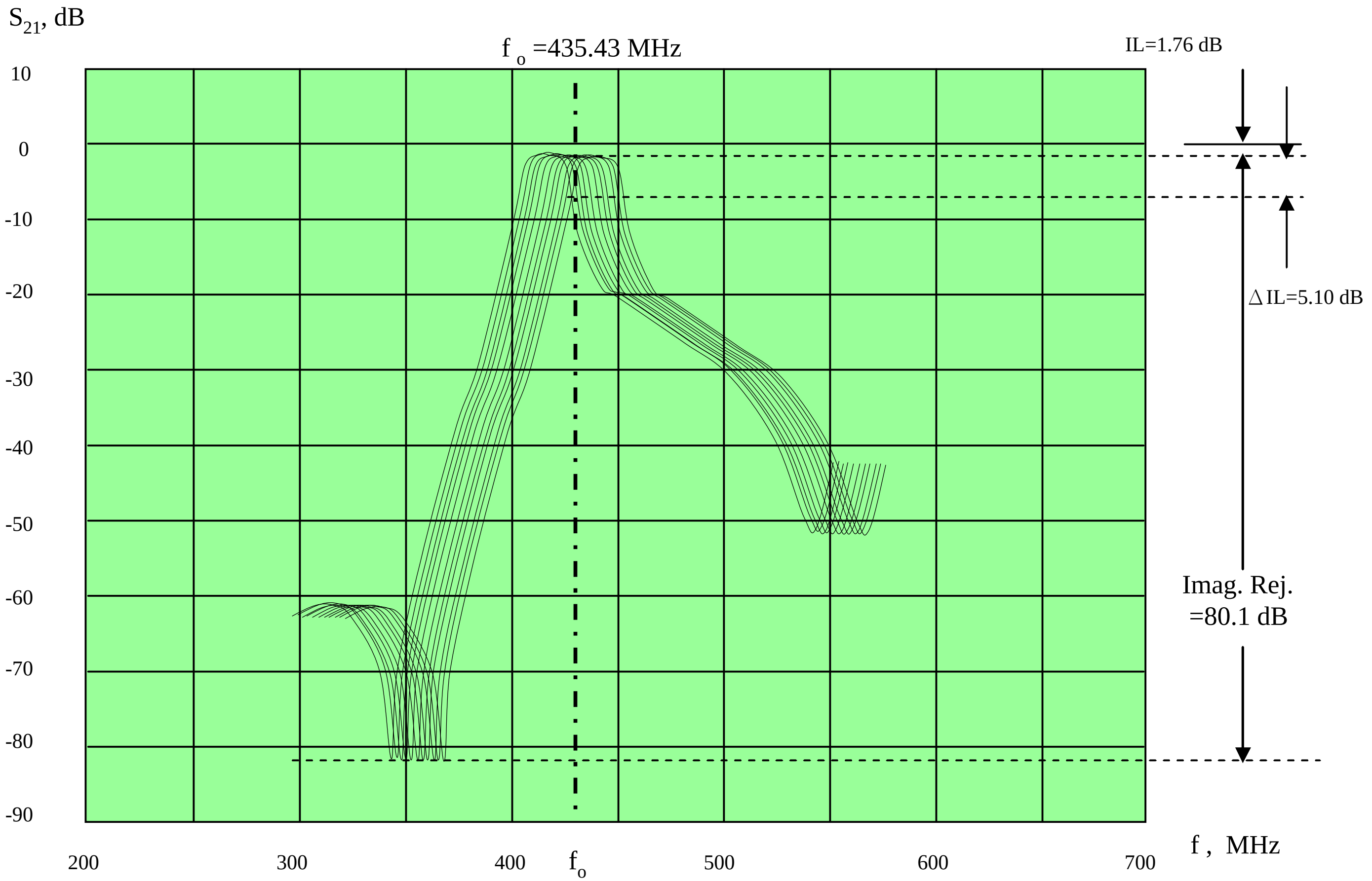


Figure 8.18 Frequency response of tunable filter with tolerance
---Bandwidth is too narrow

***   Case #2 : Bandwidth is appropriate**

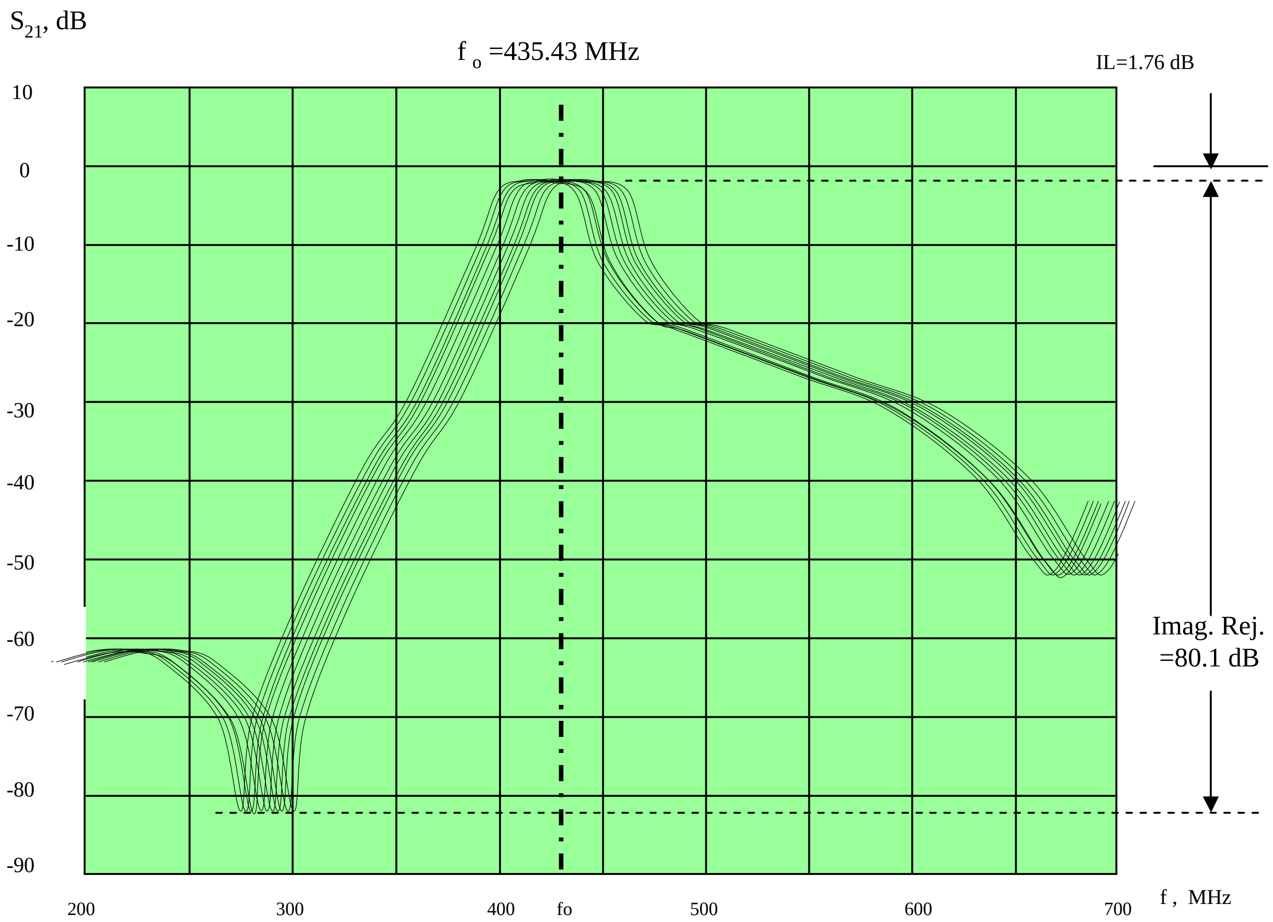


Figure 8.19   Frequency response of tunable filter with tolerance
---Bandwidth is appropriate

* **Case #1 : Bandwidth is too wide**

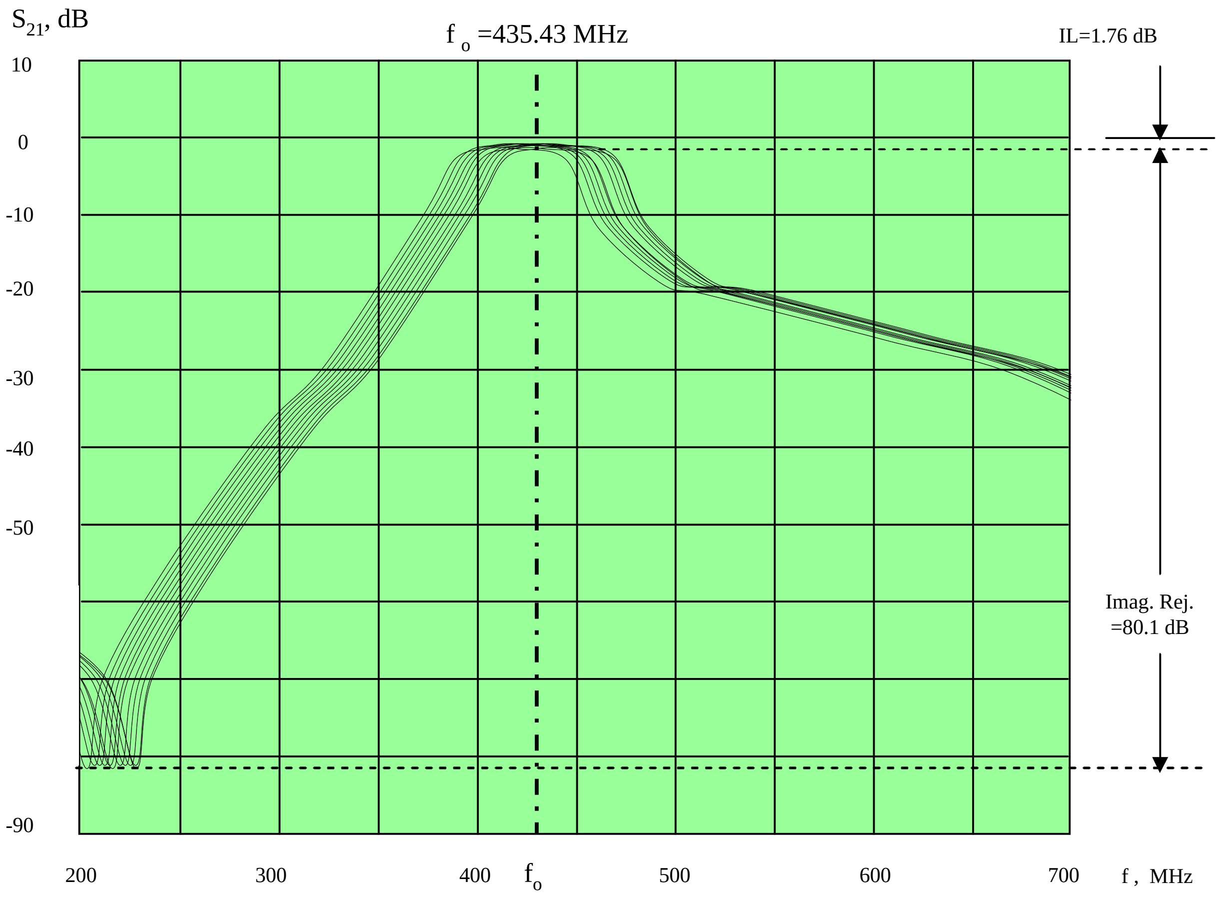
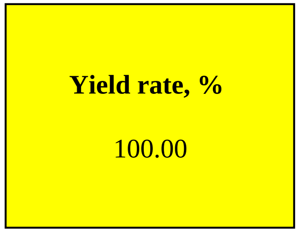


Figure 8.20 Frequency response of tunable filter with tolerance
---Bandwidth is too wide

* **Yield rate & its histogram of IL less than 2.5 dB (For case #2)**



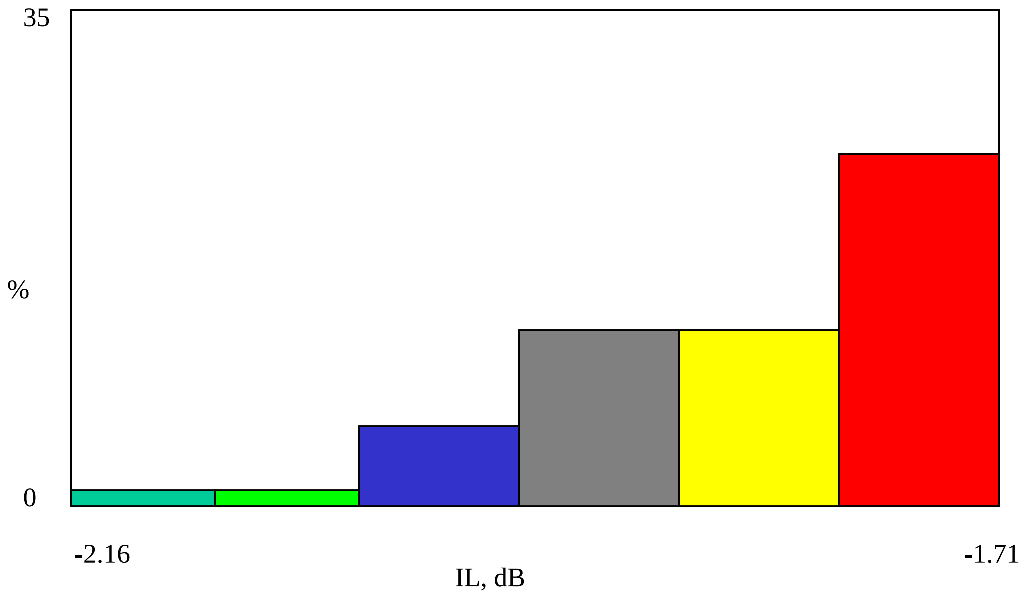
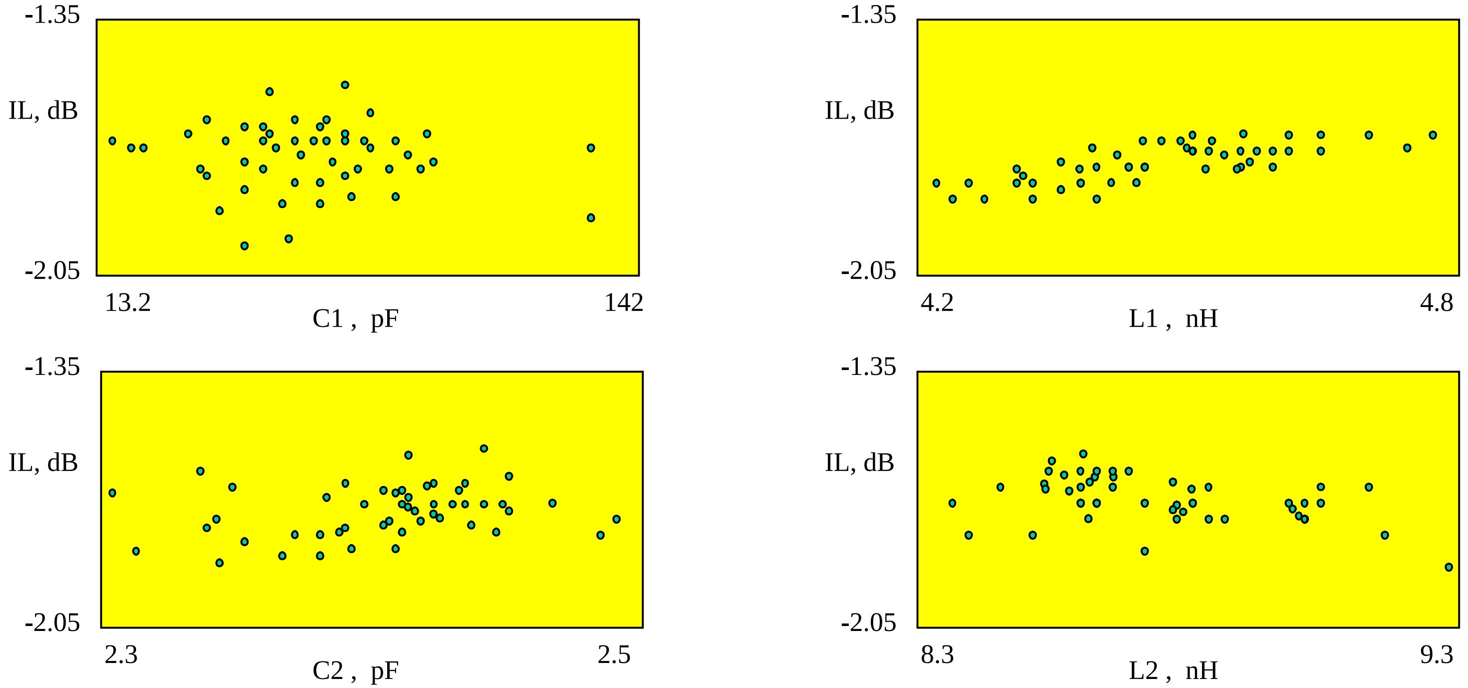
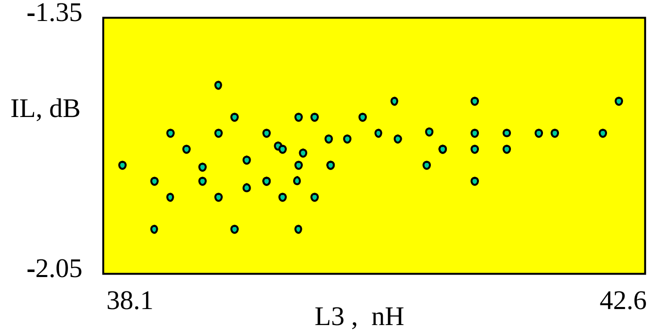


Figure 8.21 Display of insertion loss histogram and yield rate for IL<2.5*dB*

* IL performance of parts with tolerance (For case #2)





Note : L1 is not too sensitive to the IL !

Figure 8.22 The effect of individual part's value on the insertion loss

***   Yield rate & its histogram of Imag.Rej. greater than 60 dB (For case #2)**

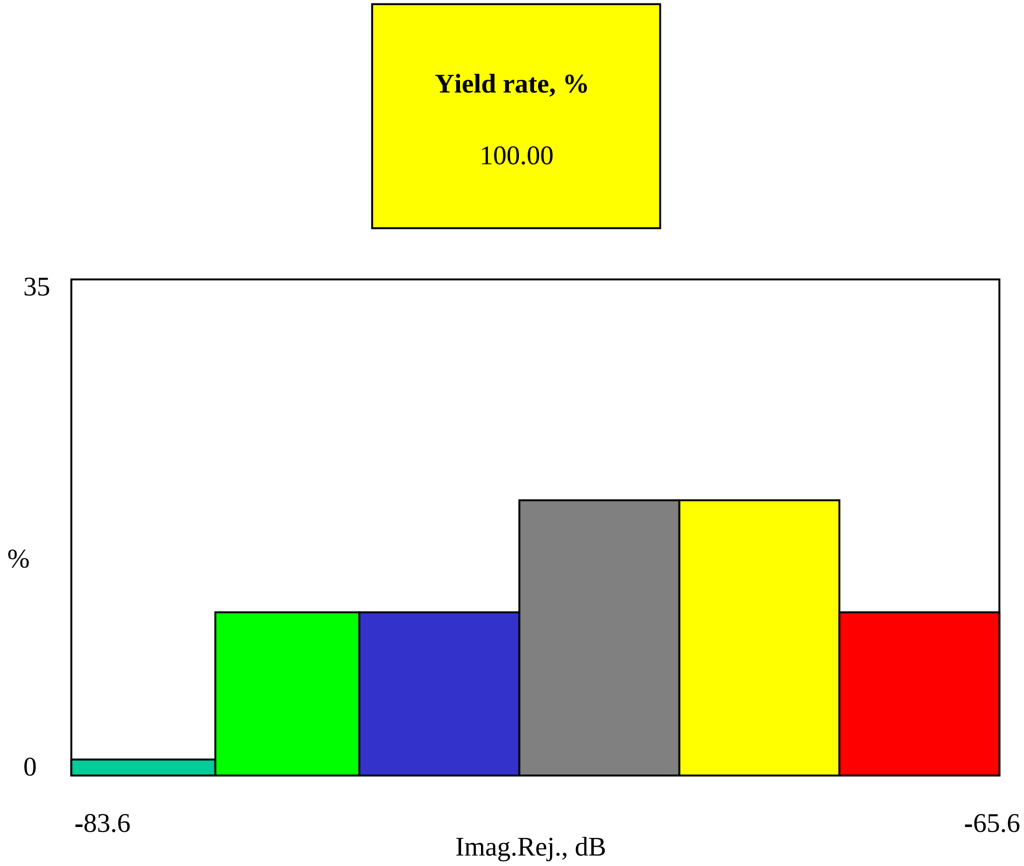
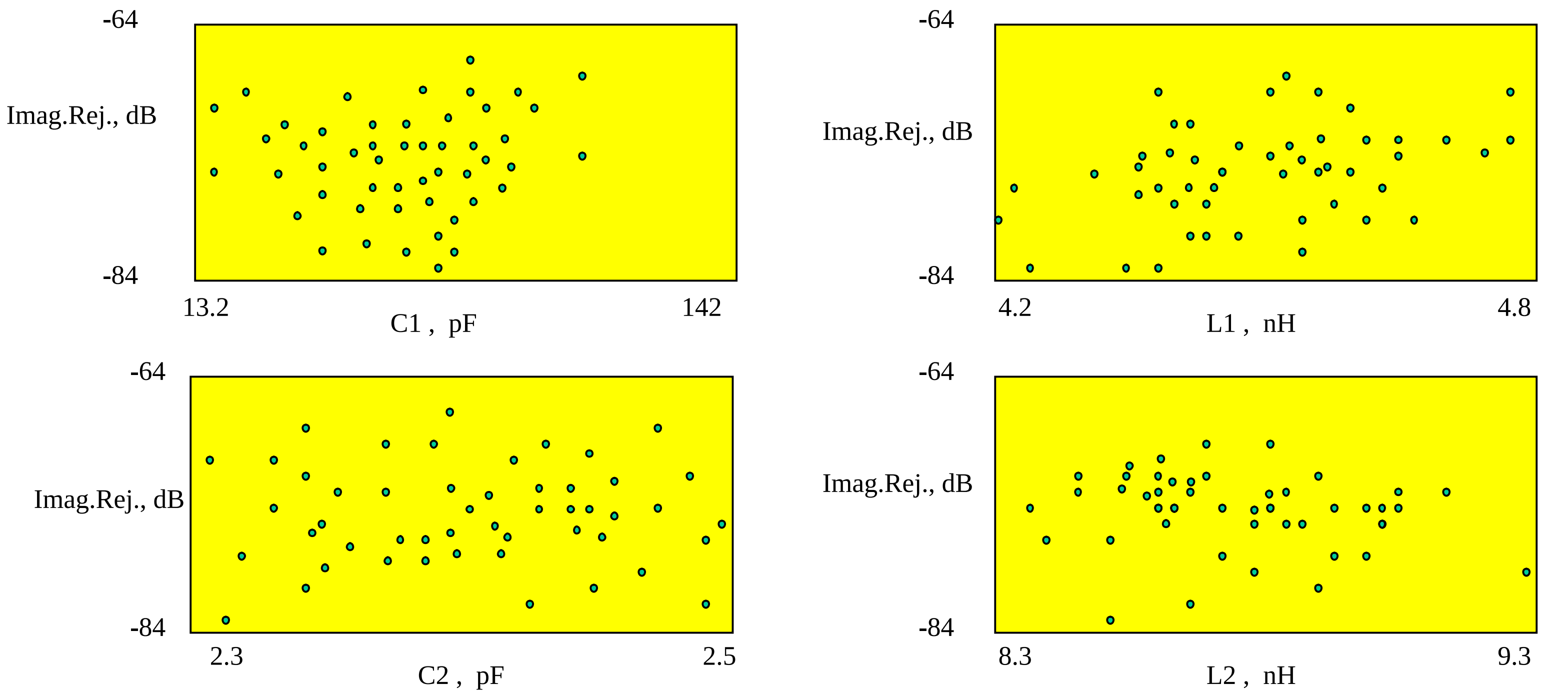
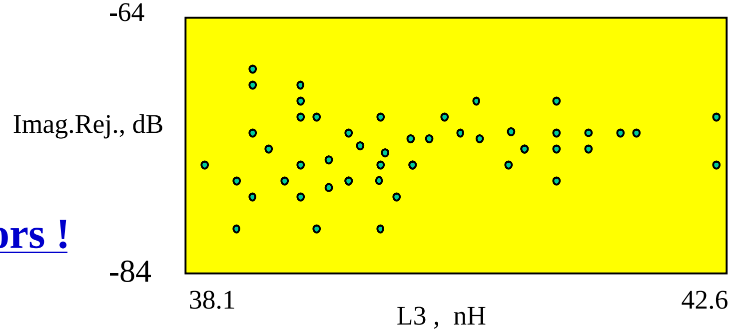


Figure 8.23   Display of image rejection histogram and yield rate for IR>60*dB*

* Image Rejection performance of parts with tolerance (For case #2)





Note : Capacitors are more sensitive to the image rejection than inductors !

Figure 8.24 The effect of individual part's value on the image rejection

5.Appendix: Table of the normal distriution

Table 8.2 Normal distriution

Z	0	1	2	3	4	5	6	7	8	9
0.0	.0000	.0040	.0080	.0120	.0160	.0199	.0239	.0279	.0319	.0359
0.1	.0398	.0438	.0478	.0517	.0557	.0596	.0636	.0675	.0714	.0754
0.2	.0793	.0832	.0871	.0910	.0948	.0987	.1026	.1064	.1103	.1141
0.3	.1179	.1217	.1255	.1293	.1331	.1368	.1406	.1443	.1480	.1517
0.4	.1554	.1591	.1628	.1664	.1700	.1736	.1772	.1808	.1844	.1879
0.5	.1915	.1950	.1985	.2019	.2054	.2088	.2123	.2157	.2190	.2224
0.6	.2258	.2291	.2324	.2357	.2389	.2422	.2454	.2486	.2518	.2549
0.7	.2580	.2612	.2642	.2673	.2704	.2734	.2764	.2794	.2823	.2852
0.8	.2881	.2910	.2939	.2967	.2996	.3023	.3051	.3078	.3016	.3133
0.9	.3135	.3186	.3212	.3238	.3264	.3289	.3315	.3340	.3365	.3389
1.0	.3413	.3438	.3461	.3485	.3508	.3531	.3554	.3577	.3599	.3621
1.1	.3643	.3665	.3686	.3708	.3729	.3749	.3770	.3790	.3810	.3830
1.2	.3849	.3869	.3888	.3907	.3925	.3944	.3962	.3980	.3997	.4015
1.3	.4032	.4049	.4066	.4082	.4099	.4115	.4131	.4147	.4162	.4177
1.4	.4192	.4207	.4222	.4236	.4251	.4265	.4279	.4292	.4306	.4319
1.5	.4332	.4345	.4357	.4370	.4382	.4394	.4406	.4418	.4429	.4441
1.6	.4452	.4463	.4474	.4484	.4495	.4505	.4515	.4525	.4535	.4545
1.7	.4554	.4564	.4573	.4582	.4591	.4599	.4608	.4616	.4625	.4633
1.8	.4641	.4649	.4656	.4664	.4671	.4678	.46	.4693	.4699	.4706
1.9	.4713	.4719	.4726	.4732	.4738	.4744	.4750	.4756	.4761	.4767

Z	0	1	2	3	4	5	6	7	8	9
2.0	.4772	.4778	.4783	.4778	.4793	.4798	.4803	.4808	.4812	.4817
2.1	.4821	.4826	.4830	.4834	.4838	.4842	.4846	.4850	.4854	.4857
2.2	.4861	.4864	.4868	.4871	.4875	.4878	.4881	.4884	.4887	.4890
2.3	.4893	.4896	.4898	.4901	.4904	.4906	.4909	.4911	.4913	.4916
2.4	.4918	.4920	.4922	.4925	.4925	.4929	.4931	.4932	4934	.4936
2.5	.4938	.4940	.4941	.4943	.4945	.4946	.4948	.4949	.4951	.4952
2.6	.4953	.4955	.4956	.4957	.4959	.4960	.4961	.4962	.4963	.4964
2.7	.4965	.4966	.4967	.4968	.4969	.4970	.4971	.4972	.4973	.4974
2.8	.4974	.4975	.4976	.4977	.4977	.4978	.4979	.4979	.4980	.4981
2.9	.4981	.4982	.4982	.4983	.4984	.4984	.4985	.4985	.4986	.4986
3.0	.4987	.4987	.4987	.4988	.4988	.4989	.4989	.4989	.4990	.4990
3.1	.4990	.4991	.4991	.4991	.4992	.4992	.4992	.4992	.4993	.4993
3.2	.4993	.4993	.4994	.4994	.4994	.4994	.4994	.4995	.4995	.4995
3.3	.4995	.4995	.4995	.4996	.4996	.4996	.4996	.4996	.4996	.4997
3.4	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4998
3.5	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998
3.6	.4998	.4998	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999
3.7	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999
3.8	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999
3.9	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000

$$f(z) = \int_0^z \frac{e^{-\frac{x^2}{2}}}{\sqrt{2p}} dx = \frac{1}{2} erf\left(\frac{z}{\sqrt{2}}\right)$$

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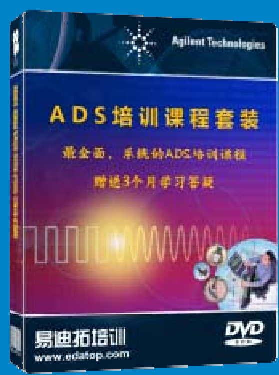

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