

Strumentazione Biomedica II

Seminario:

**Radar UWB per il monitoraggio remoto
dell'attività respiratoria**

Erika Pittella

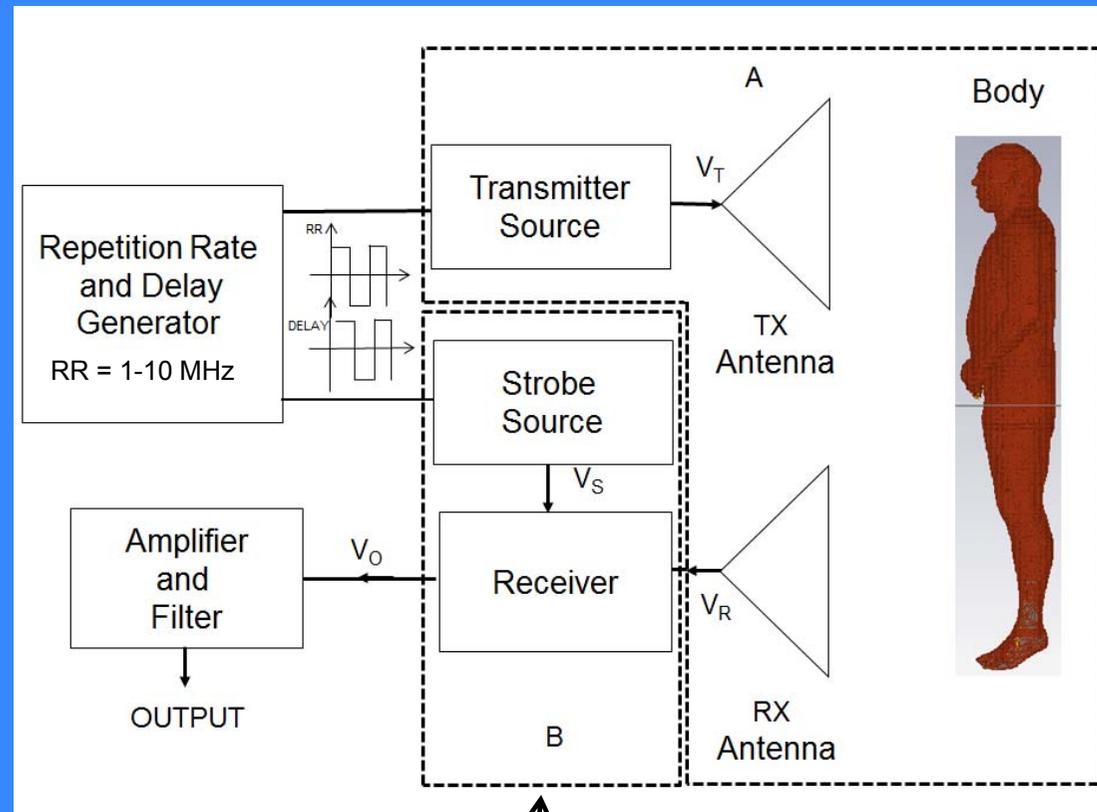


SAPIENZA
UNIVERSITÀ DI ROMA

Sommario

- **Struttura del radar UWB**
- **Modello circuitale**
- **Progetto dei sottosistemi**
- **Realizzazione dei sottosistemi**
- **Risultati**
- **Assemblaggio e test del radar UWB completo**
- **Salute dell'uomo**
- **Sviluppi futuri**

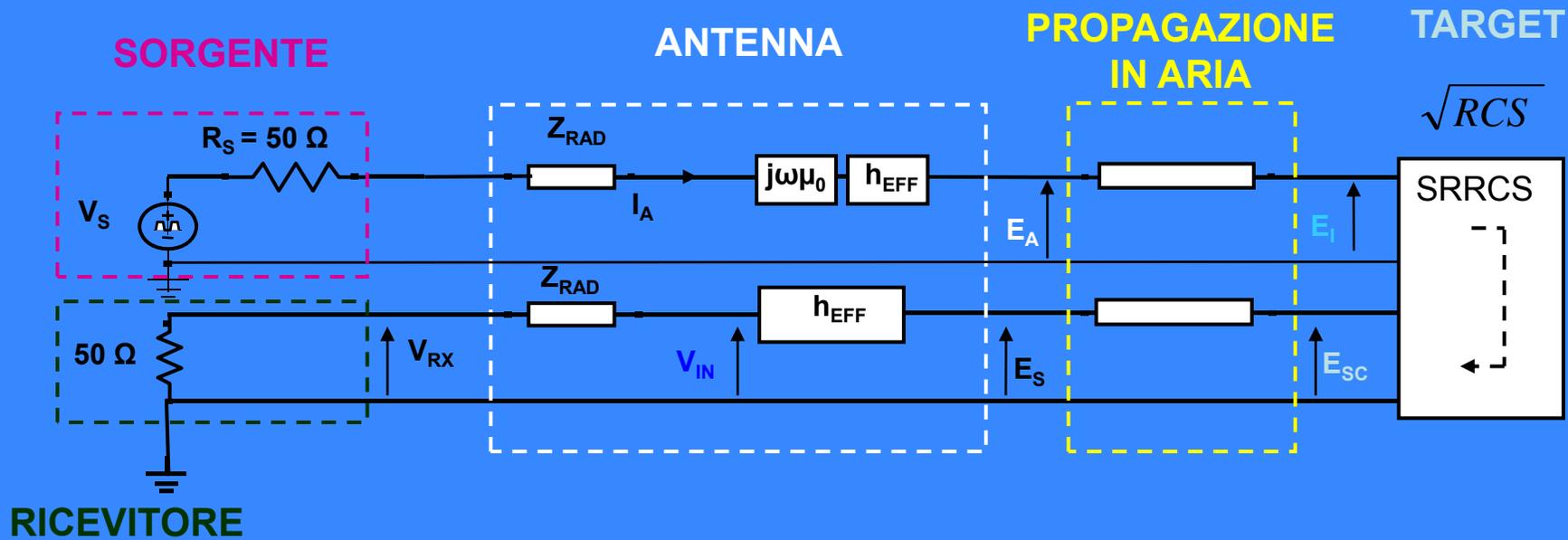
Struttura del radar UWB



A
Sistema radar

B:
Ricevitore

Schema del sistema radar



PROPRIETA' TRASMETTENTI
DELL'ANTENNA

$$\underline{\mathbf{E}}(r, \theta, \varphi) = j\omega\mu_0 \underline{\mathbf{N}}(\theta, \varphi) \frac{e^{-jkr}}{4\pi r}$$

$$\mathbf{E}(r) = j\omega\mu_0 h_{\text{EFF}} \frac{\mathbf{I}_A e^{-jkr}}{4\pi r} = \mathbf{E}_A \frac{e^{-jkr}}{4\pi r}$$

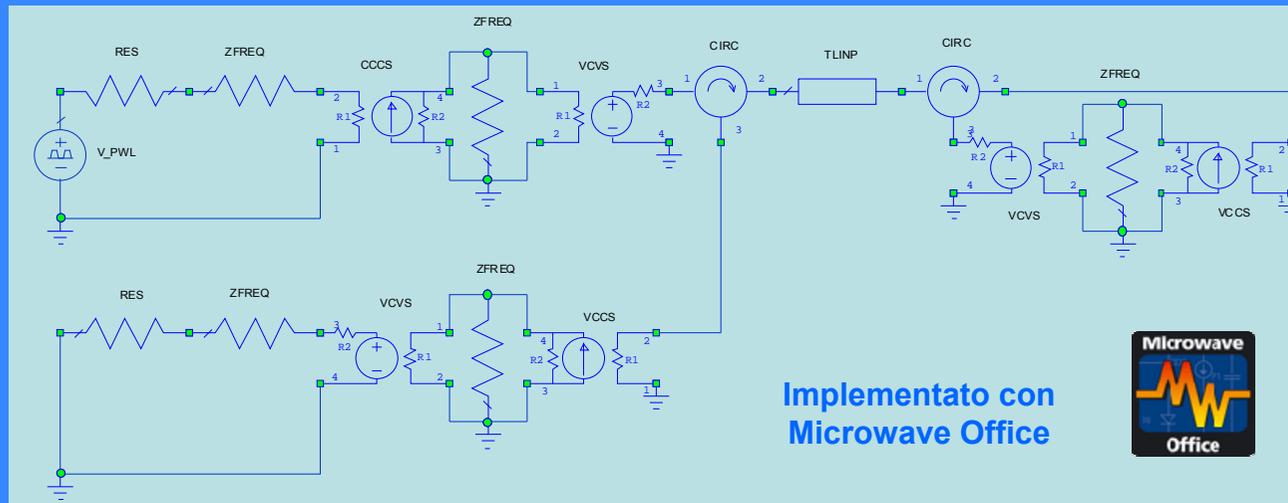
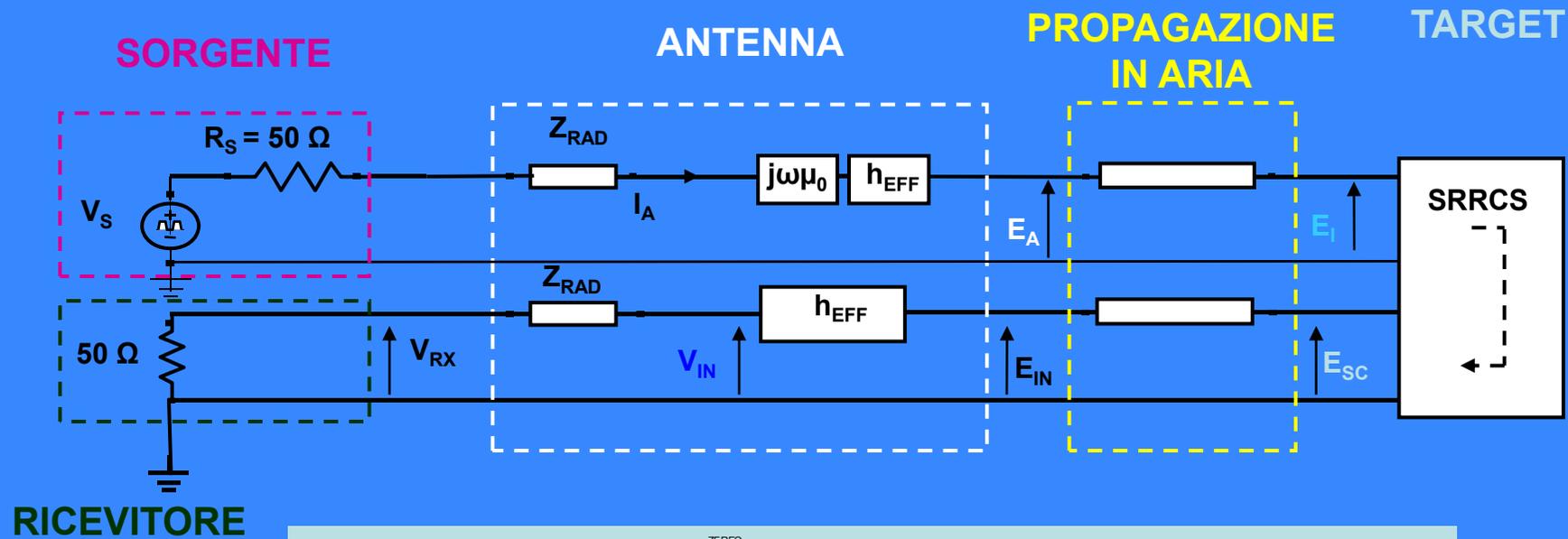
CAMPO
SCATTERATO

$$\mathbf{E}_{\text{SC}} = \frac{\sqrt{RCS}}{r\sqrt{4\pi}} \mathbf{E}_I$$

PROPRIETA' RICEVENTI
DELL'ANTENNA

$$\mathbf{V}_{\text{IN}} = h_{\text{EFF}} \mathbf{E}_S$$

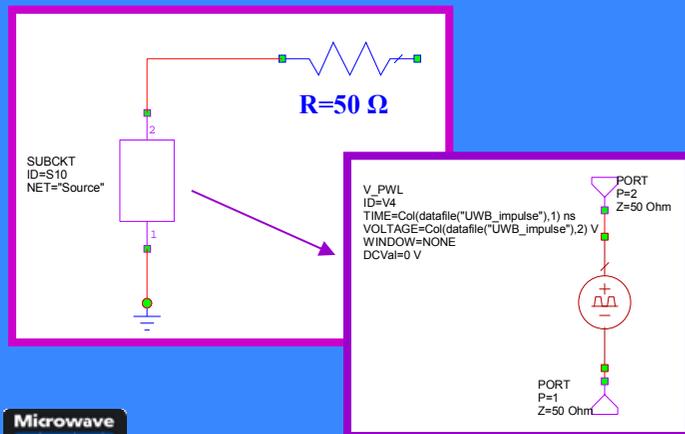
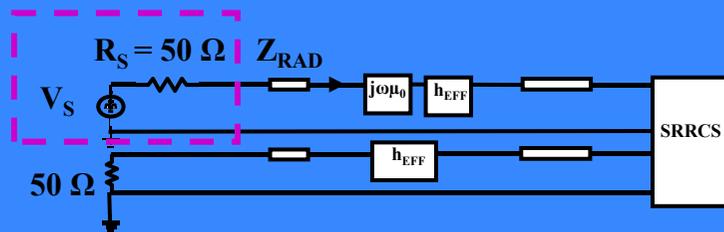
Implementazione del modello



S. Pisa, P. Bernardi, M. Cavagnaro, E. Pittella, E. Piuzei, "Monitoring of cardio-pulmonary activity with UWB radar: a circuitual model", Proc. 2008 Asia-Pacific Symposium on EMC & 19th Int. Zurich Symp. on Electromagnetic Compatibility, Singapore, pp. 224-227, May 2008.

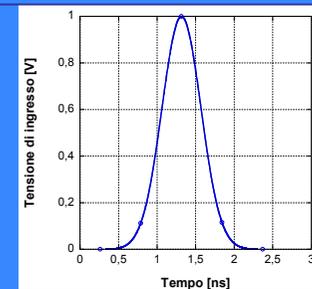
Modello della sorgente

- La sorgente è stata simulata all'interno del CAD attraverso un generatore che consente di inserire i vari tipi di forme d'onda di interesse.
- L'impedenza interna della sorgente è stata assunta pari a 50Ω .



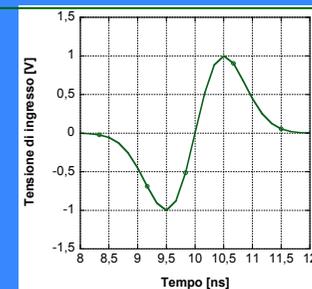
Impulso Gaussiano

$$V_s(t) = \hat{V} \cdot e^{-\frac{1}{2} \left(\frac{t-t_0}{\sigma} \right)^2}$$



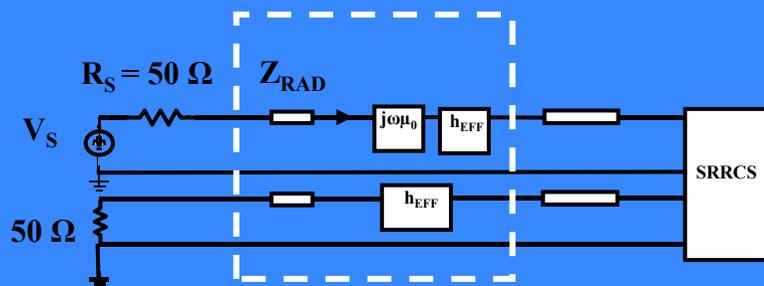
Monociclo

$$V_s(t) = \hat{V} \cdot \sqrt{e} \cdot \frac{(t_0 - t)}{\sigma} e^{-\frac{1}{2} \left(\frac{t-t_0}{\sigma} \right)^2}$$



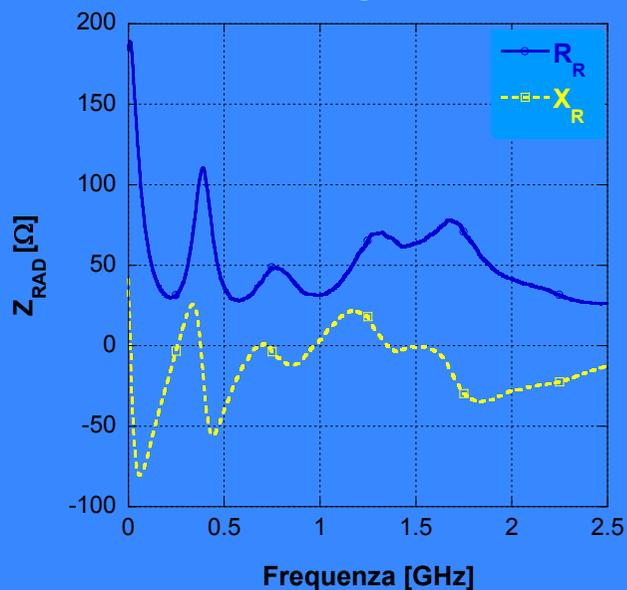
δ
 δt

Modello dell'antenna



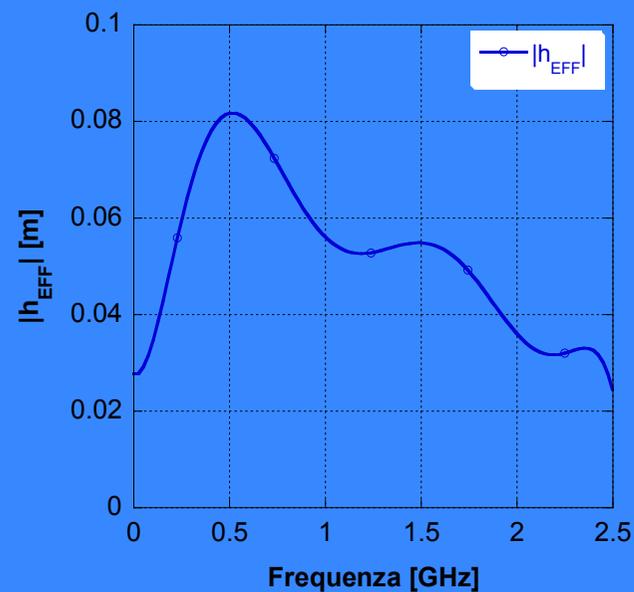
$$Z_{RAD} = Z_0 \frac{1 + \Gamma}{1 - \Gamma}$$

Il coefficiente di riflessione è stato ottenuto dalle misure con l'analizzatore vettoriale Agilent PNA E8363B

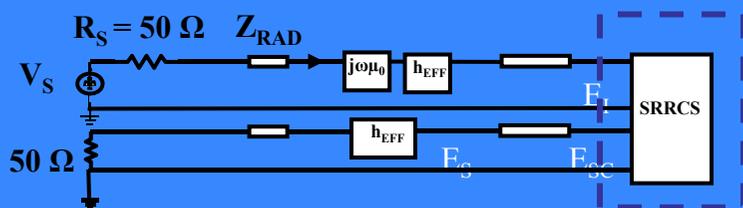


$$|h_{EFF}| = 2 \cdot \sqrt{\frac{R_R}{R_0}} \cdot 10^{-\frac{AF}{20}}$$

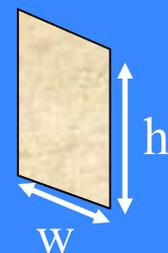
AF è riportato nei datasheet dell'antenna



Modello della Radar Cross Section

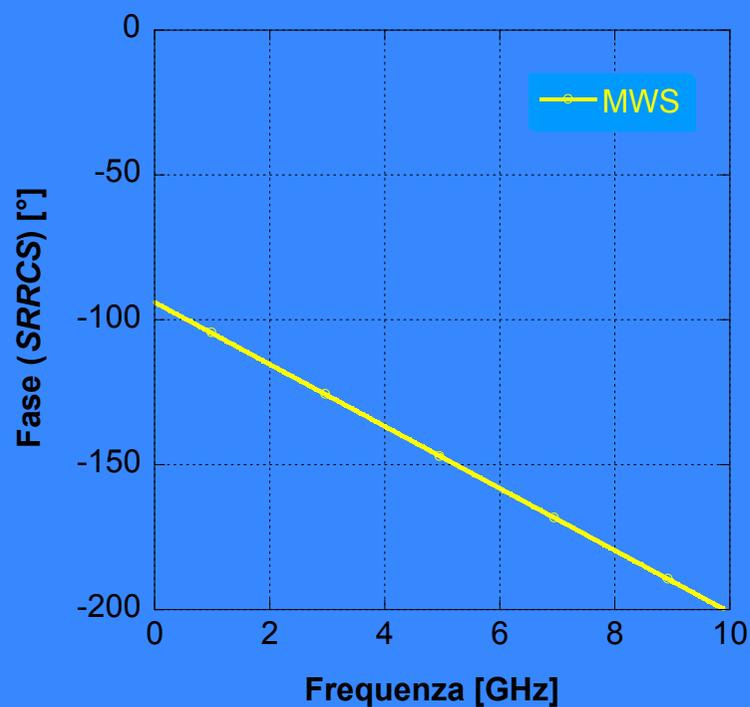
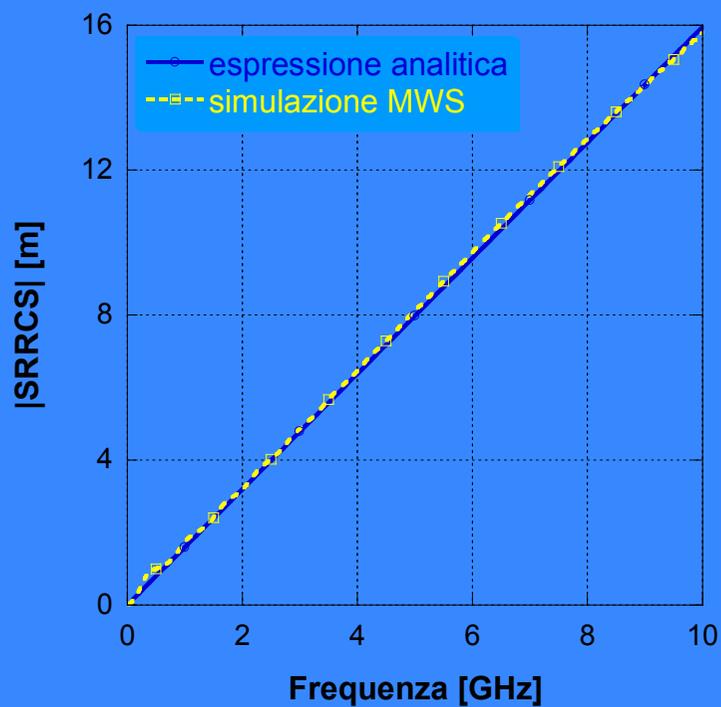


$$SRRCS = |SRRCS| e^{j\varphi_{SRRCS}} = \frac{E_S}{E_I} r \sqrt{4\pi} e^{j\beta r}$$

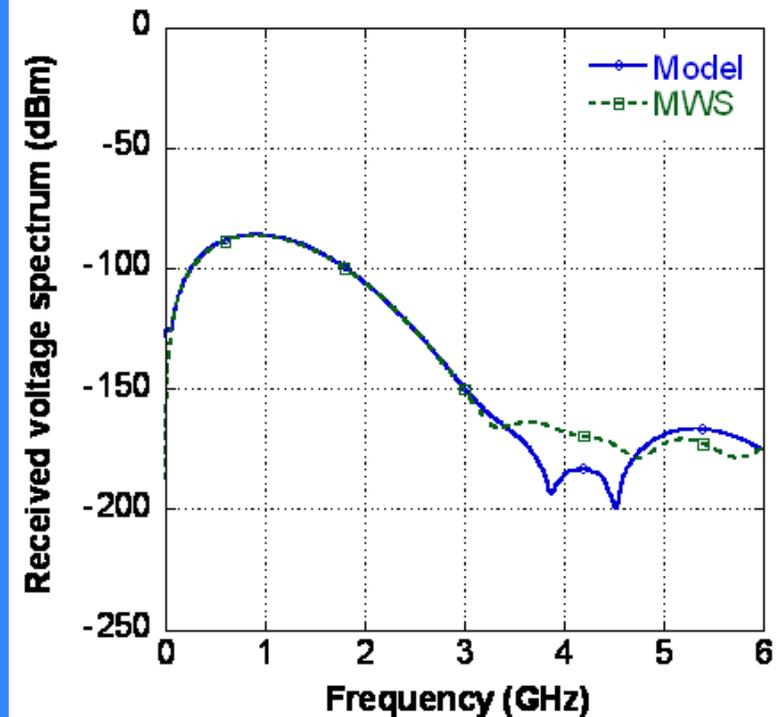
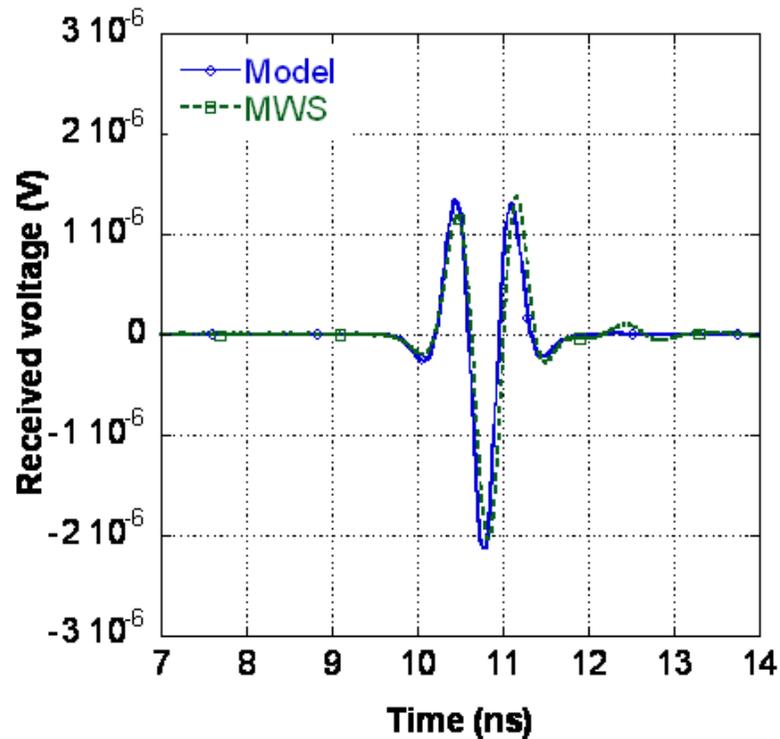


Espressione analitica

$$|SRRCS| = \sqrt{4\pi} \left(\frac{w \cdot h}{\lambda} \right)$$



Convalida numerica



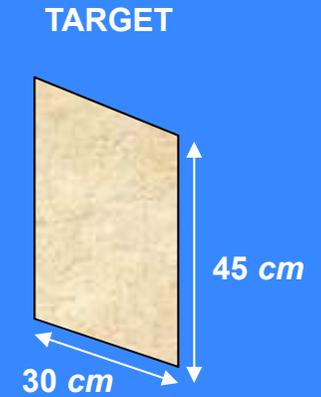
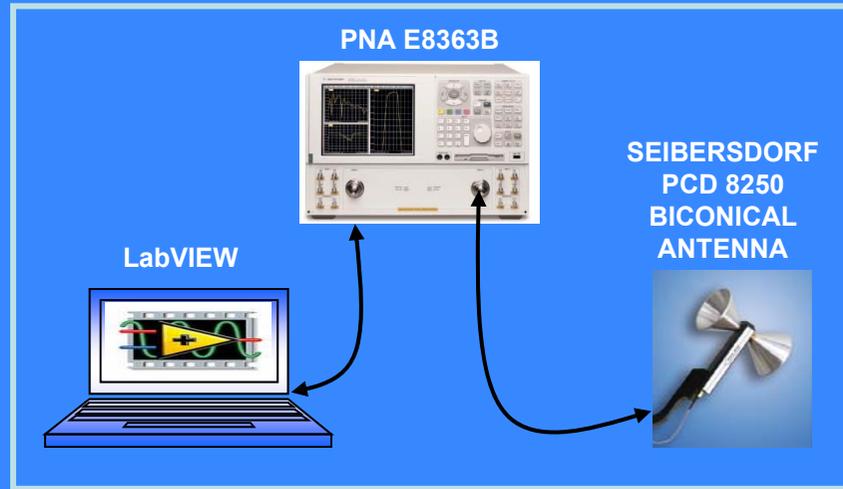
MWS: Microwave Studio by CST

✓ **OTTIMO ACCORDO TRA SIMULAZIONI EM E MODELLO CIRCUITALE**

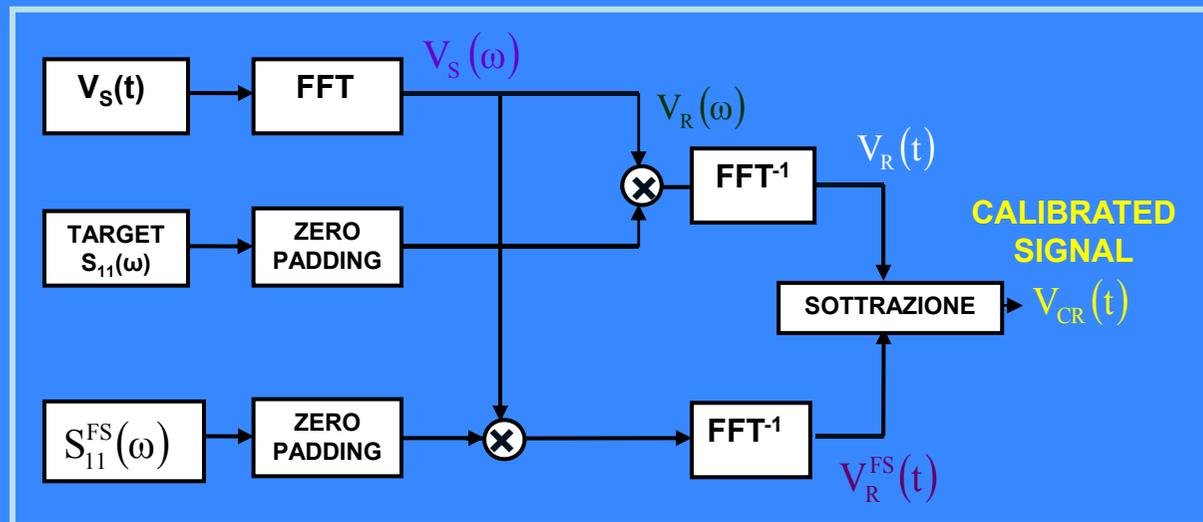
E. Pittella, P. Bernardi, M. Cavagnaro, S. Pisa, and E. Piuze, "Numerical and Experimental Validation of a Circuitual Model of a UWB Radar for Breath Activity Monitoring", in Abstract Collection of BIOEM 2009 Davos (Joint Meeting of the Bioelectromagnetics Society and the European BioElectromagnetics Association), Davos, Switzerland, paper P-217, June 2009.

Set-up sperimentale

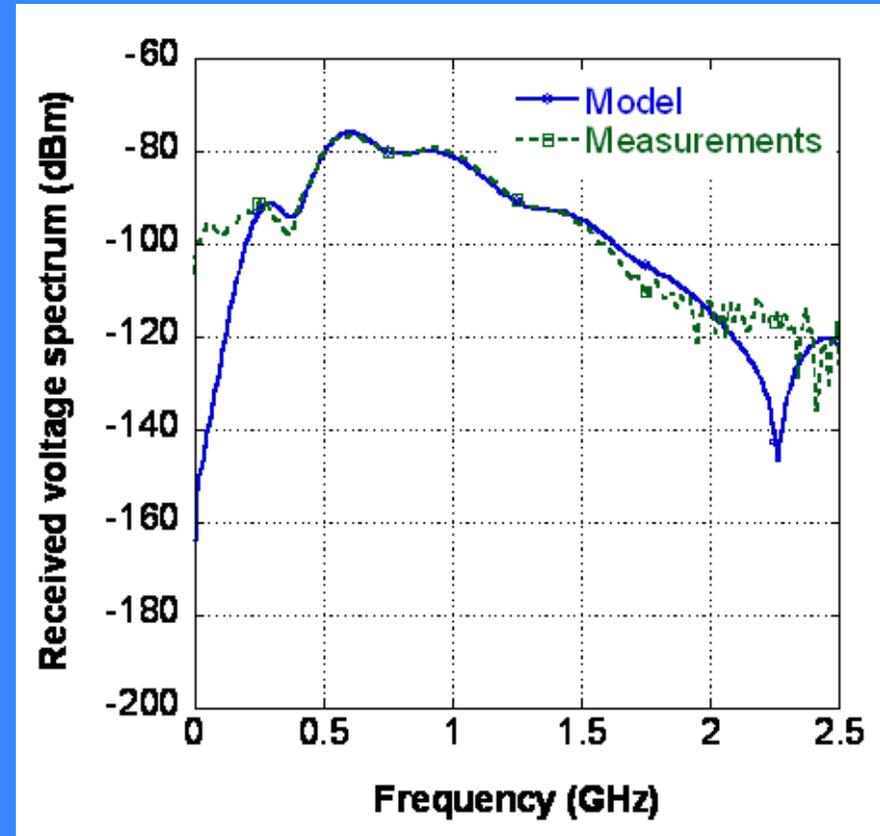
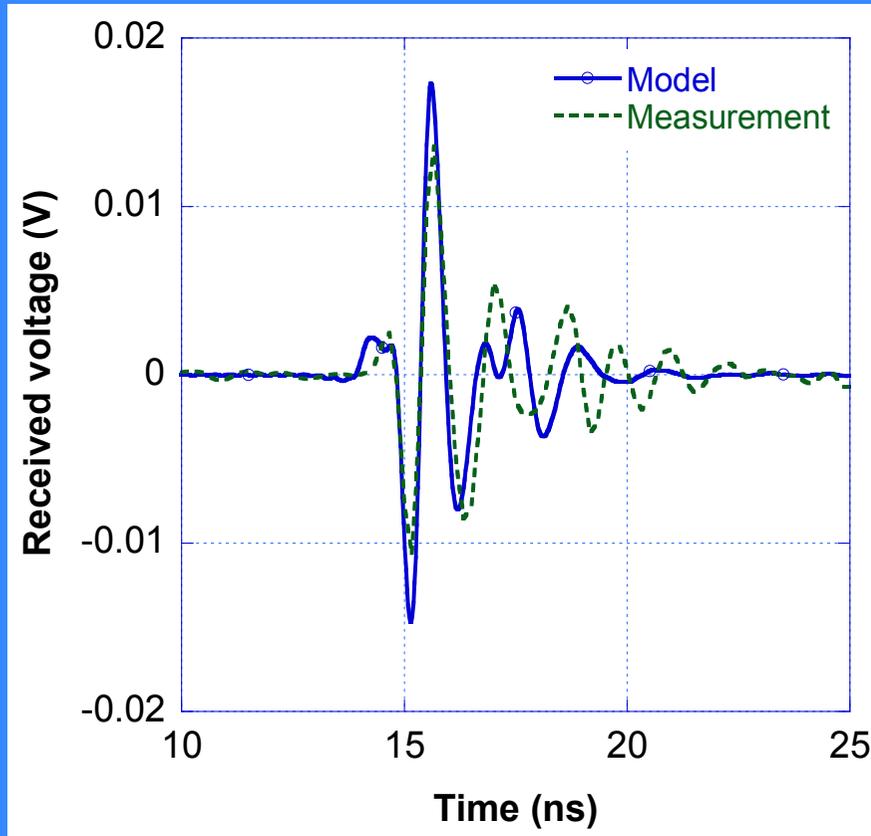
Sistema
rifletto-metrico nel
dominio del tempo



Schema a
blocchi



Convalida sperimentale

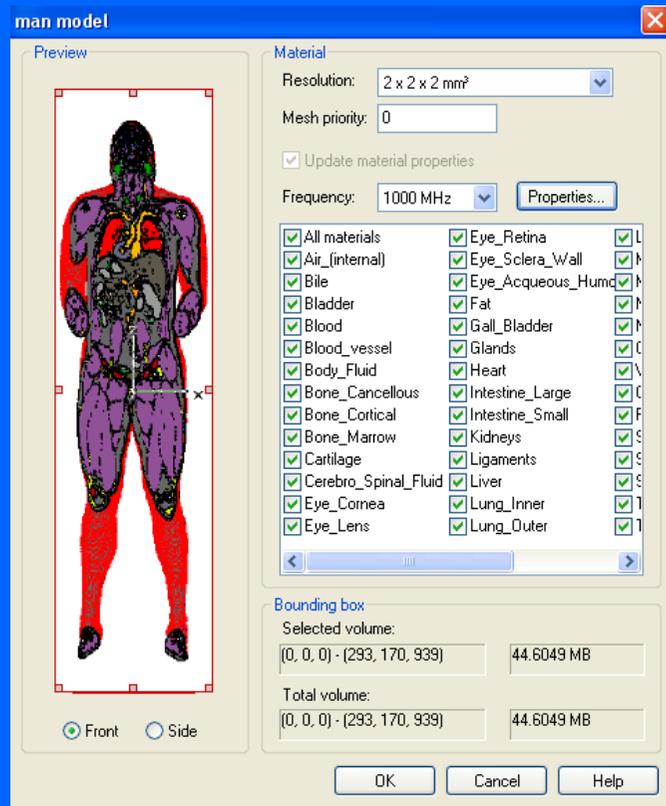


✓ **BUON ACCORDO TRA MISURE E MODELLO CIRCUITALE**

E. Pittella, P. Bernardi, M. Cavagnaro, S. Pisa, and E. Piuzei, "Numerical and Experimental Validation of a Circuitual Model of a UWB Radar for Breath Activity Monitoring", in Abstract Collection of BIOEM 2009 Davos (Joint Meeting of the Bioelectromagnetics Society and the European BioElectromagnetics Association), Davos, Switzerland, paper P-217, June 2009.

Modello dell'uomo - RCS (1/2)

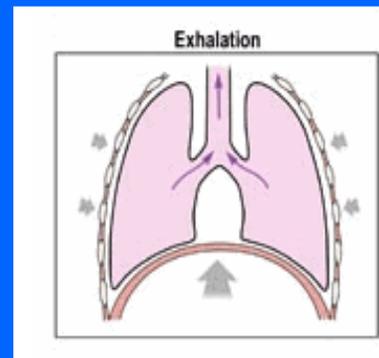
VISIBLE HUMAN (VH) MODEL



SUBJECT IN THE RESTING STATE (RS)

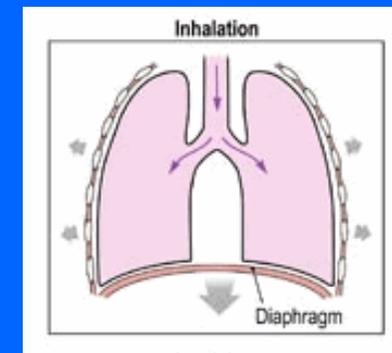
	Height	Weight
VH	188 cm	103 kg
Scaled VH	188 cm	80 kg

END OF THE EXHALATION PHASE



$$l_{EX} \cong 3800 \text{ cm}^3$$

END OF THE INHALATION PHASE



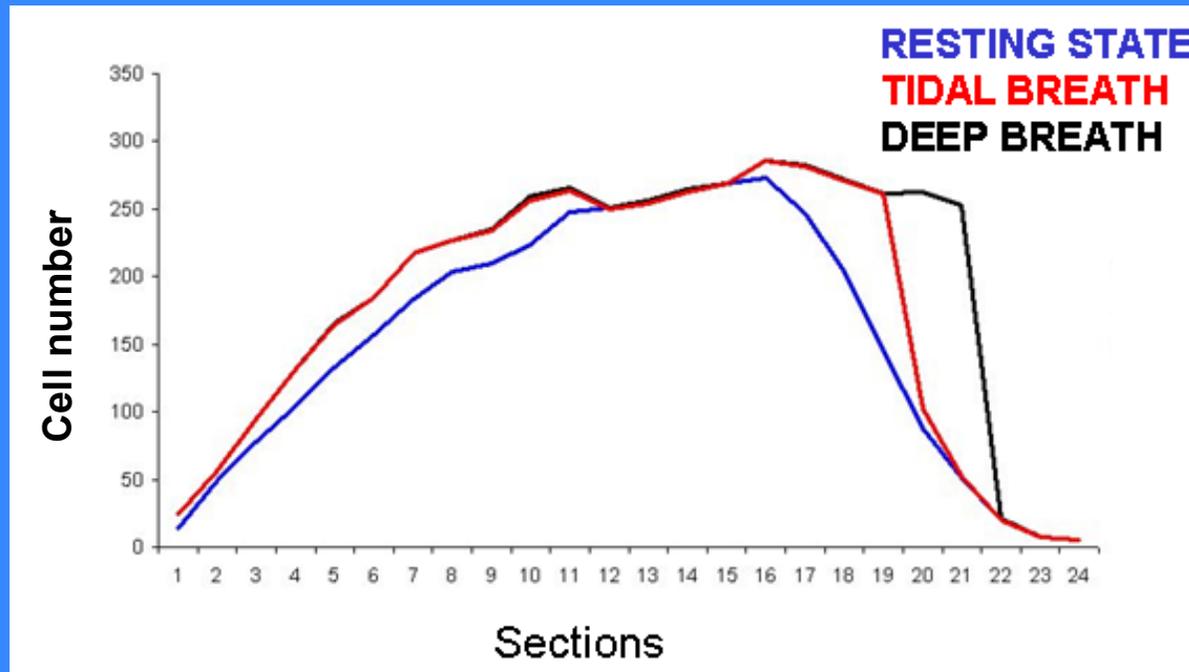
$$l_{IN} \cong l_{EX} + \begin{cases} 500 \text{ cm}^3 \text{ (TB)} \\ 860 \text{ cm}^3 \text{ (DB)} \end{cases}$$

[Marieb 2007]

Due nuovi modelli
di uomo

- TIDAL BREATH (TB) + 500 cm³
- DEEP BREATH (DB) + 860 cm³

Modello dell'uomo - RCS (1/2)

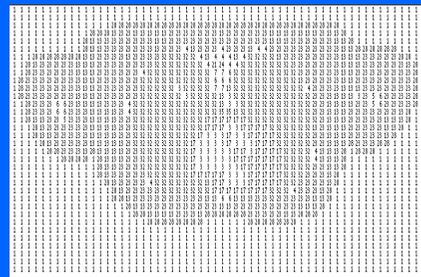


[Marieb 2007]

ANATOMIC AXIAL IMAGE



NUMERICAL DATA SET

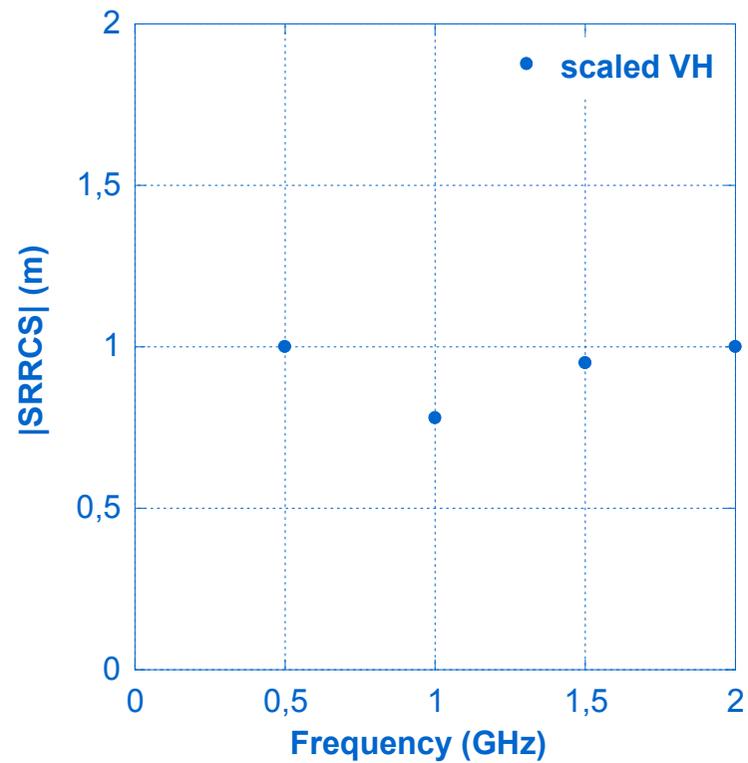


PLOT BY MATLAB



E. Pittella, P. Bernardi, M. Cavagnaro, S. Pisa, and E. Piuzei, "Modelling of Breath Activity Monitoring by Ultra Wideband Radar System", in Atti XVIII RiNEm Benevento, Italy.

Risultati RCS



$$\phi_{SR RCS}(f) = -90^\circ - m f_{GHz}$$

$m = 887, 892, 895$ for RS, TB, DB rispettivamente

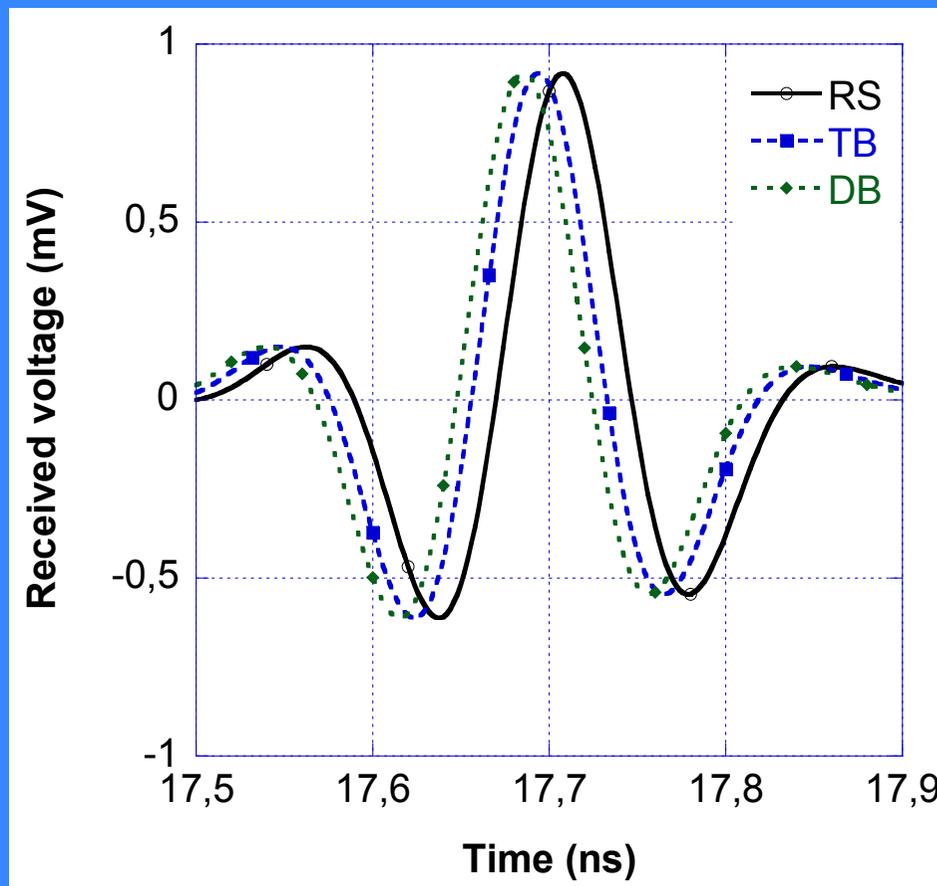
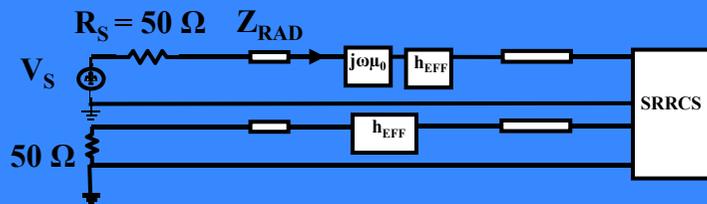
Segnale ricevuto con il modello

SOURCE 4th-derivative

$$V_s(t) = V_0 \left(\frac{(t-t_0)^4}{\sigma^8} - \frac{6(t-t_0)^2}{\sigma^6} + \frac{3}{\sigma^4} \right) e^{-\frac{(t-t_0)^2}{2\sigma^2}}$$

DISTANZA ANTENNA - VH

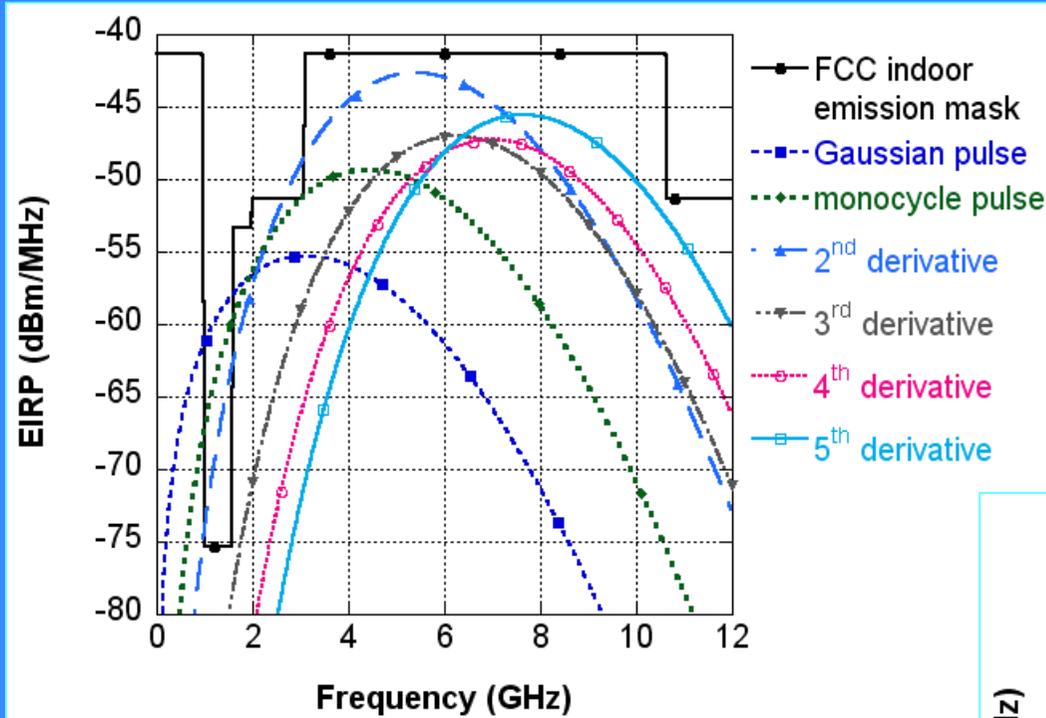
$d = 2.5 \text{ m}$



	Time delay
RS - TB	14 ps
RS - DB	22 ps

The obtained results point out the ability of the proposed radar to **discriminate** between the positions of the human thorax during respiration.

Rispetto delle maschere di emissione

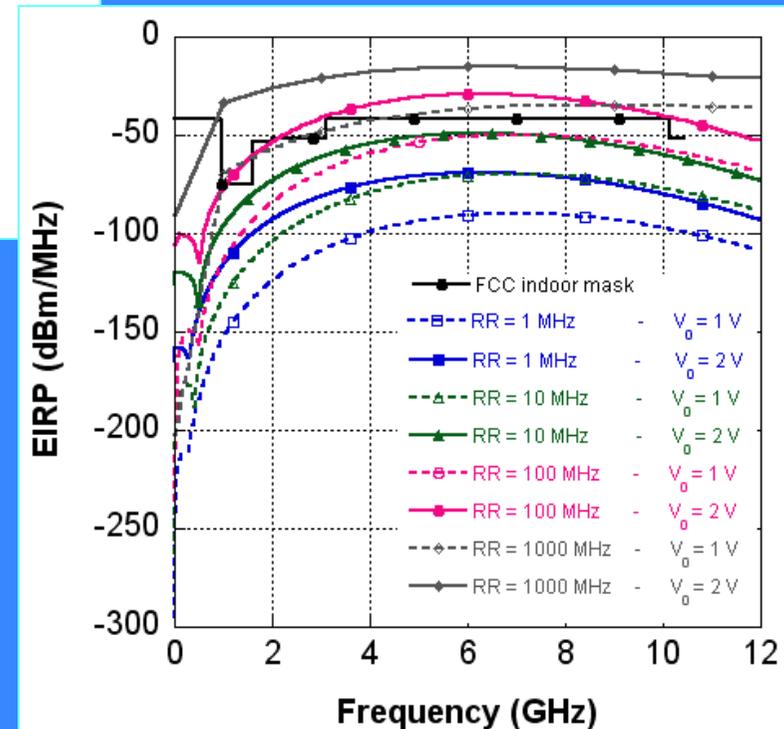


$$V_s(t) = V_0 e^{-\frac{(t-t_0)^2}{2\sigma^2}} \quad V_0 = 1 \text{ V} \quad \sigma = 51 \text{ ps}$$

$$f_r = 10 \text{ MHz}$$

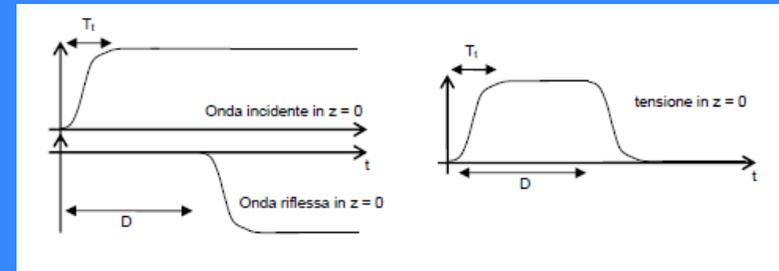
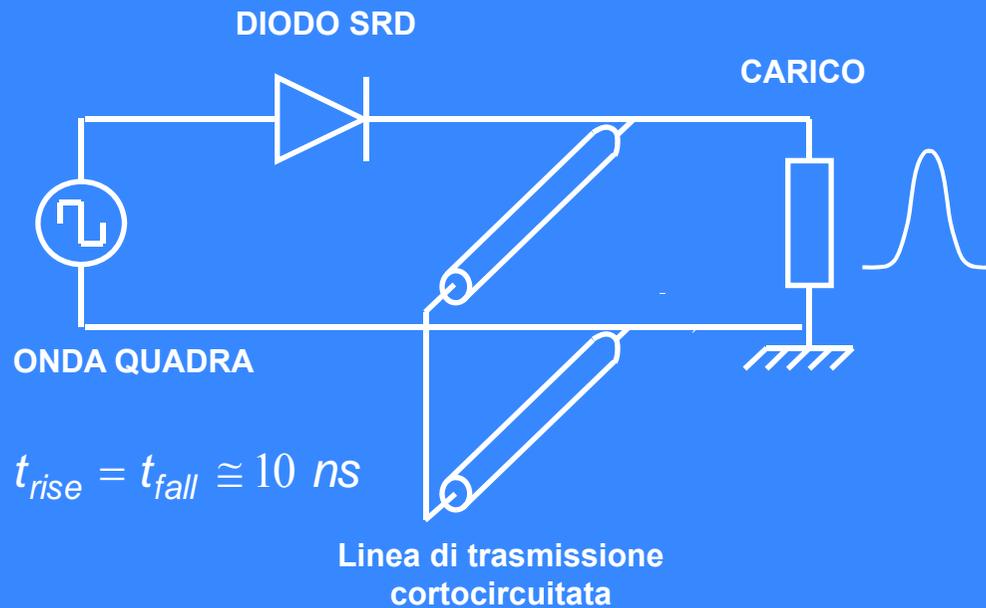
✓ 4th-derivative

$$V_s(t) = V_0 \left(\frac{(t-t_0)^4}{\sigma^8} - \frac{6(t-t_0)^2}{\sigma^6} + \frac{3}{\sigma^4} \right) e^{-\frac{(t-t_0)^2}{2\sigma^2}}$$



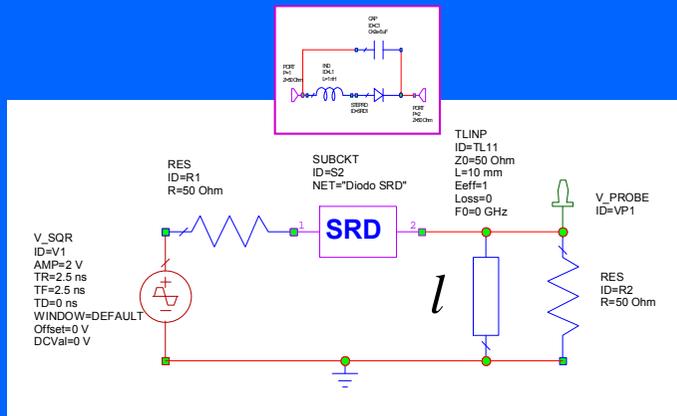
Progetto della sorgente UWB

- ✓ Impulso Gaussiano
- ✓ Monociclo
- ✓ Derivate di ordine superiore

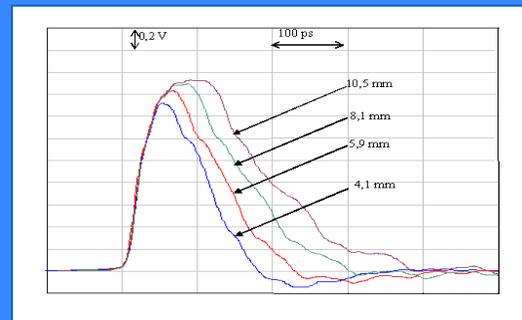
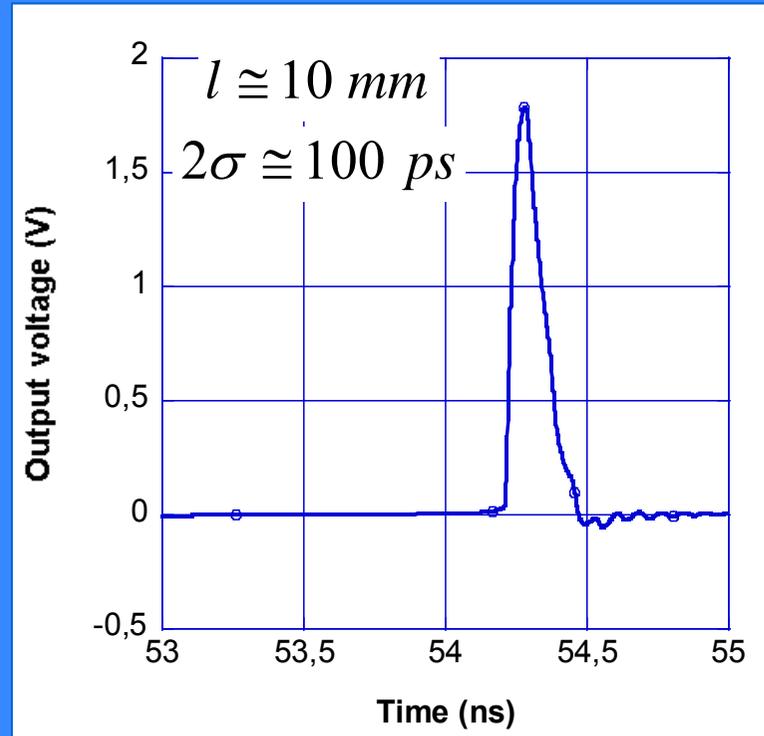
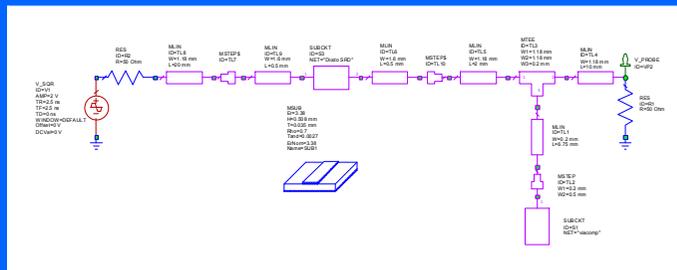


Impulso Gaussiano

Schematico circuito



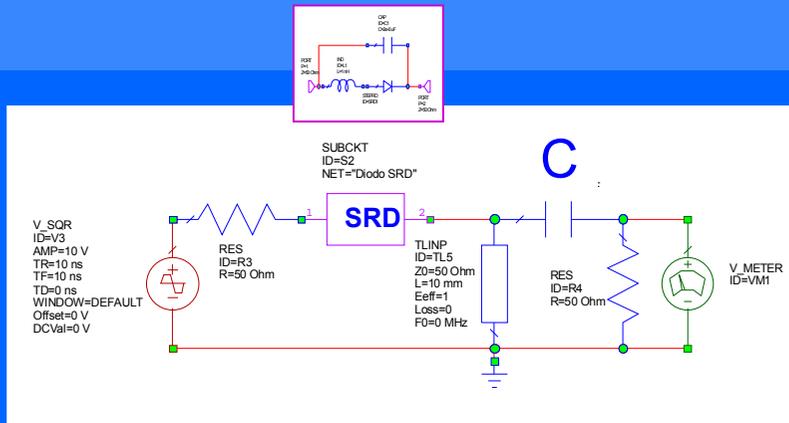
Layout



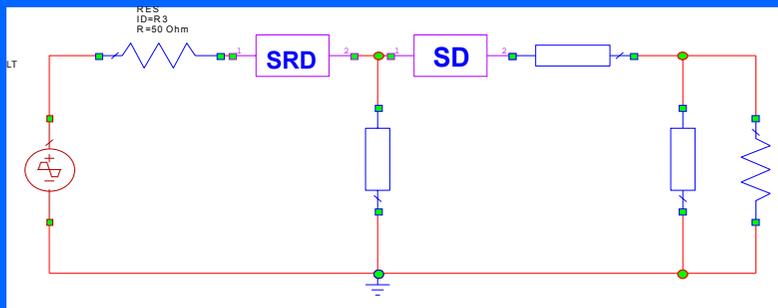
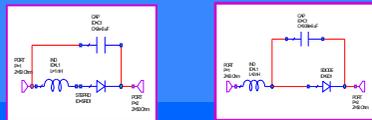
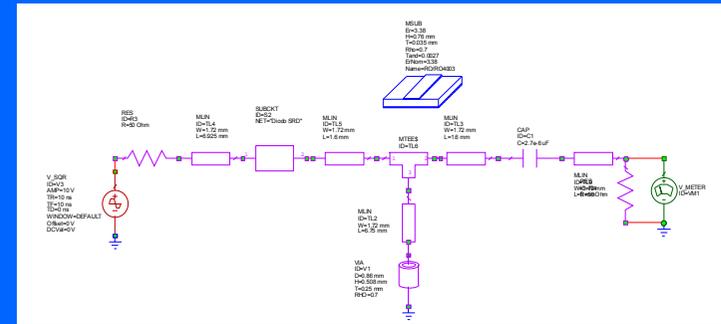
Variando “*l*”

Monociclo

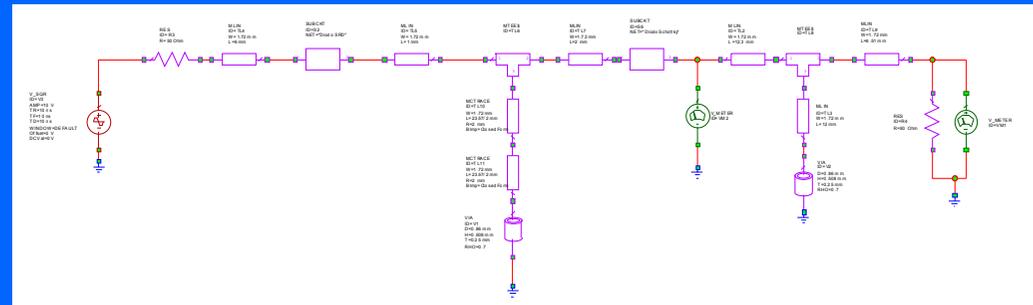
Schematico circuito



Schematico layout

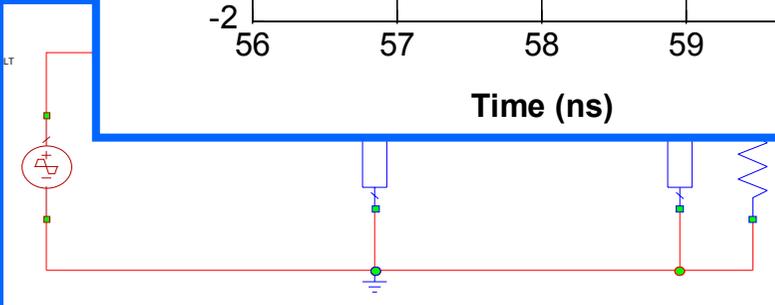
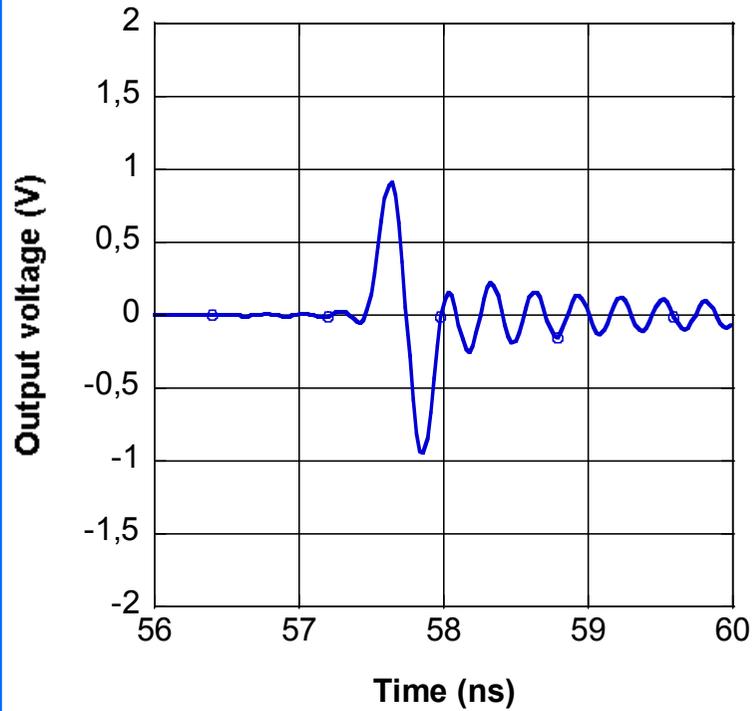


2 linee in corto circuito

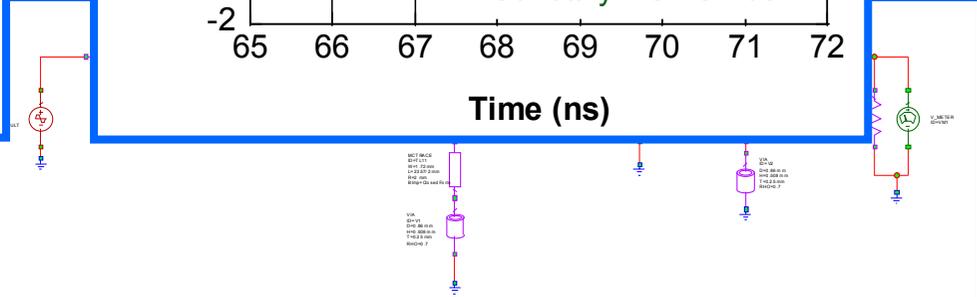
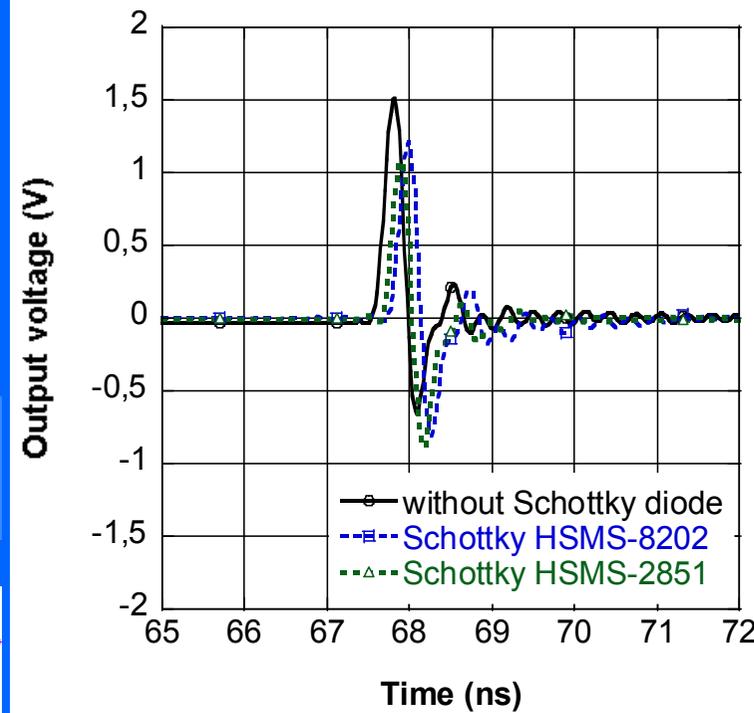


Monociclo

Monociclo con C

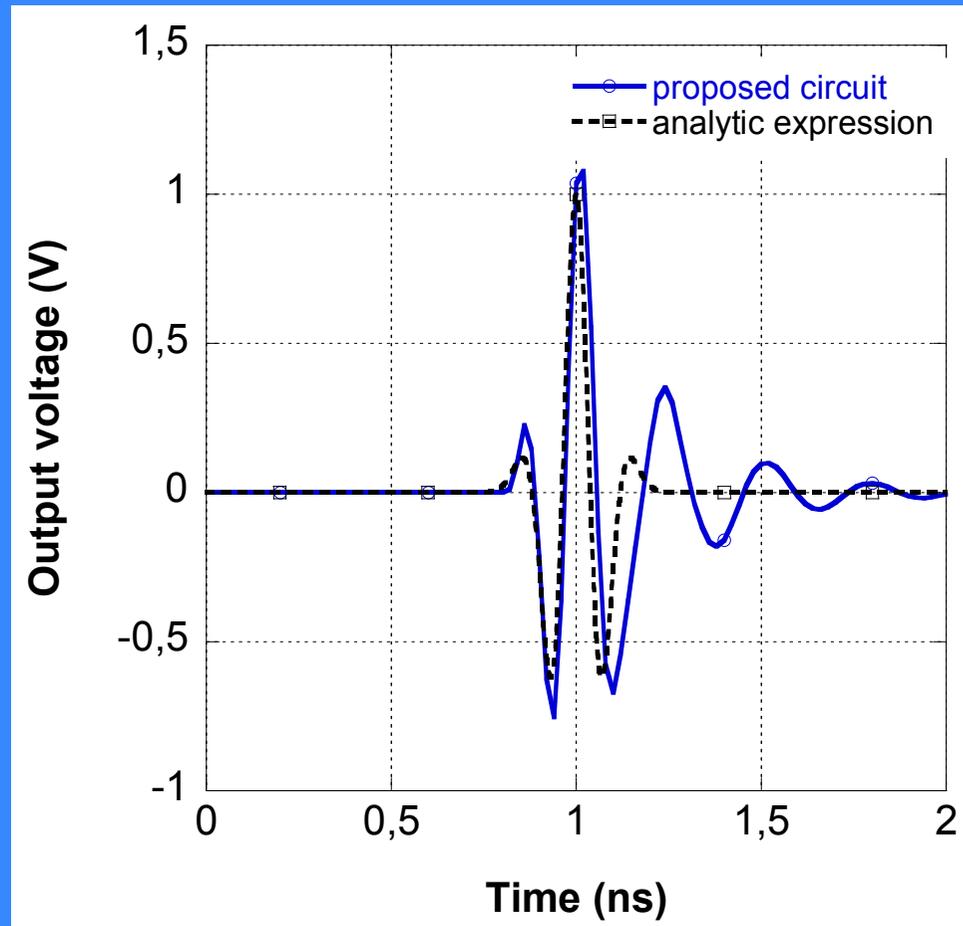
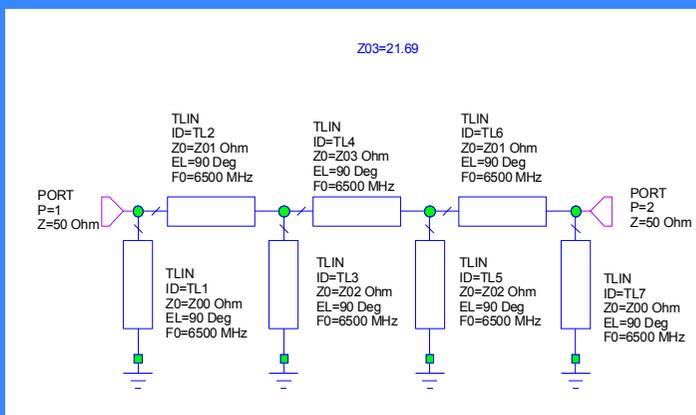
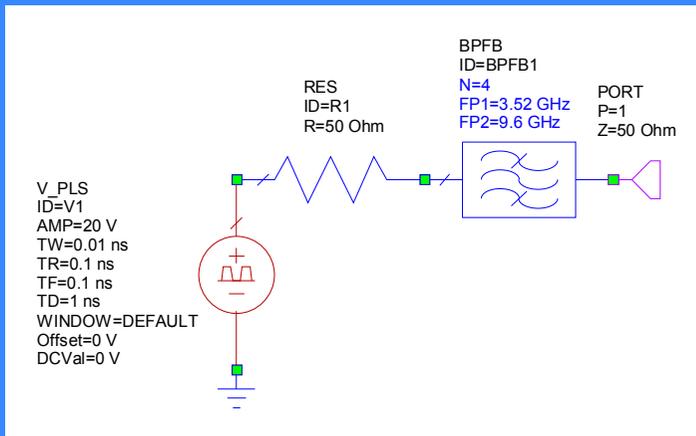


Monociclo con corto circuito



Derivate di ordine superiore

$$V_s(t) = V_0 \left(\frac{(t-t_0)^4}{\sigma^8} - \frac{6(t-t_0)^2}{\sigma^6} + \frac{3}{\sigma^4} \right) e^{-\frac{(t-t_0)^2}{2\sigma^2}}$$



Realizzazione

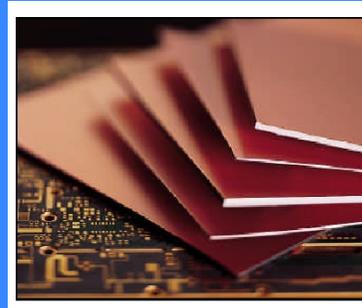
1 file .ger

Dal CST o dal MWO

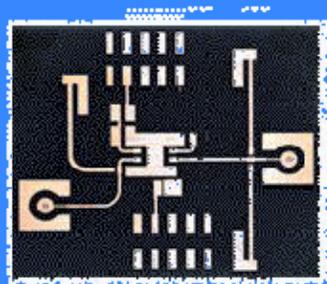
2 IsoPro



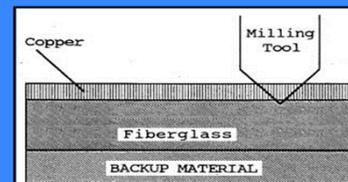
3 Microforgia



Microforgia



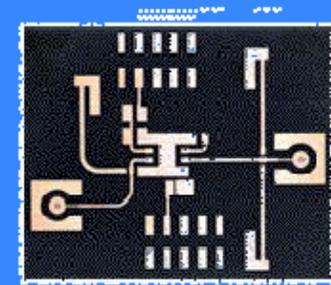
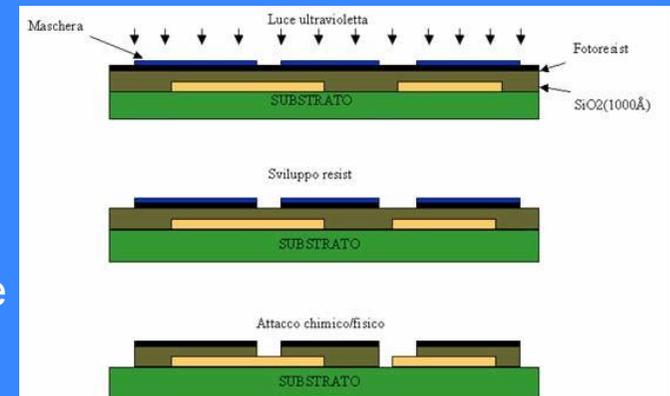
Circuito realizzato



La punta rimuove il rame dal bordo del substrato

Tecnica fotolitografica

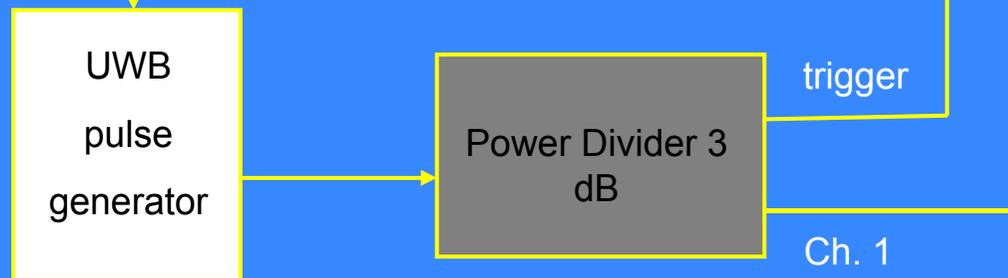
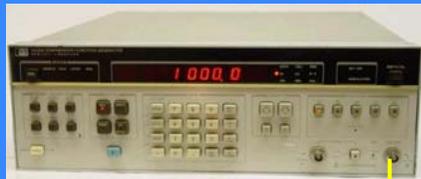
- a) Si disegna una maschera (geometria del conduttore)
- b) La maschera viene riportata su un film plastico che deve bloccare la luce ultravioletta nelle zone del conduttore (maschera positiva)
- c) Si stende un sottile strato di fotoresist sulla superficie del rame (tipicamente $0.5 \mu\text{m}$). Il fotoresist è un materiale che si modifica se esposto alla luce ultravioletta
- d) Si poggia la maschera sul fotoresist e la si espone alla luce ultravioletta
- e) Si toglie la maschera e si pone la piastra in un liquido sviluppatore che elimina il fotoresist che è stato esposto alla luce ultravioletta
- f) Si pone la piastra in un bagno sviluppatore (normalmente cloruro ferrico) che provoca la rimozione del rame dove non è protetto dal fotoresist. Si pone la piastra in un solvente (fissatore) per rimuovere il fotoresist non esposto



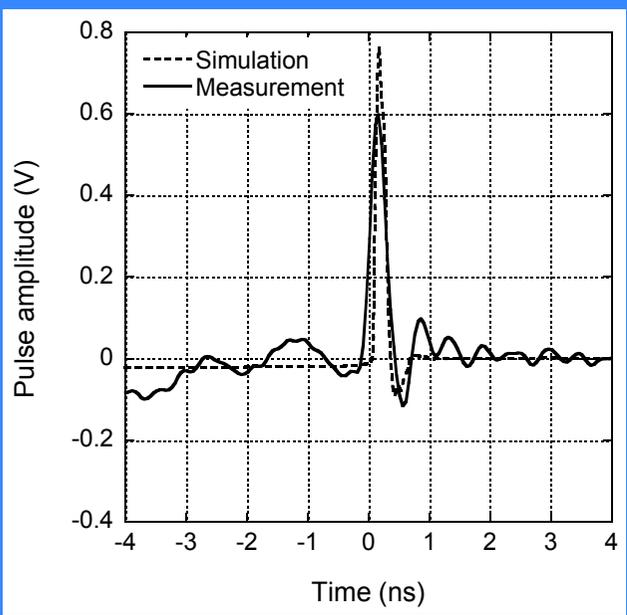
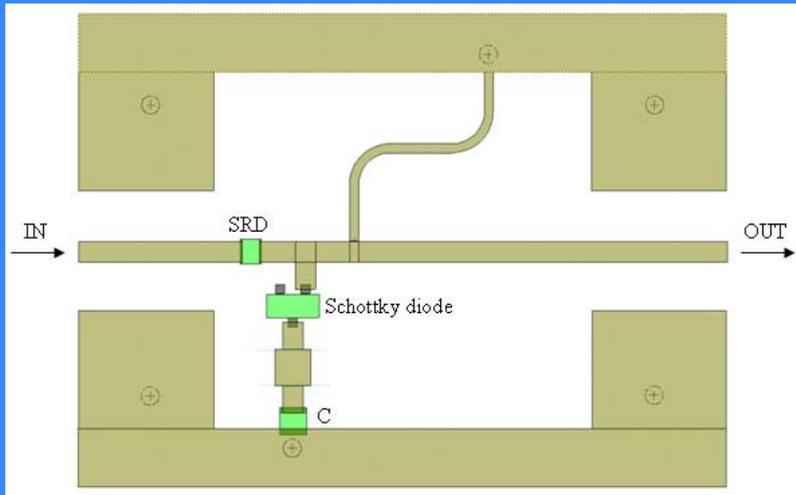
risoluzioni di $1 \mu\text{m}$

Set-up Misure

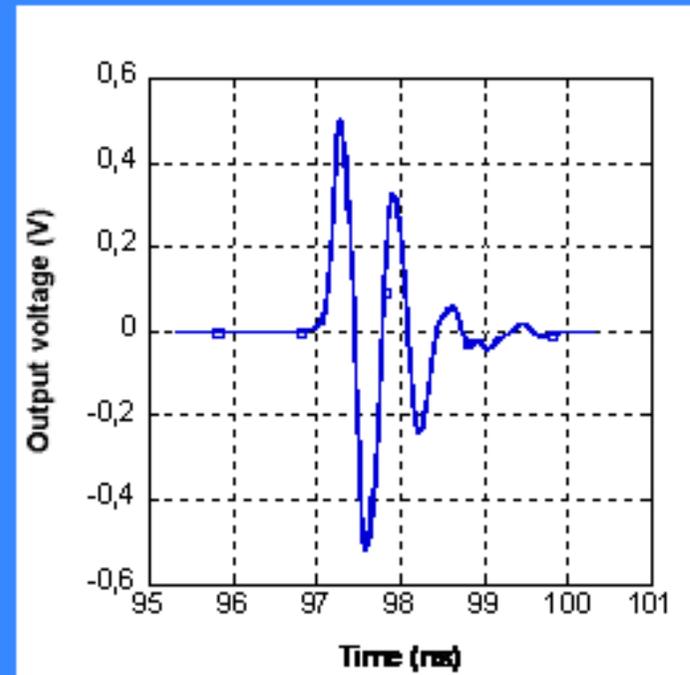
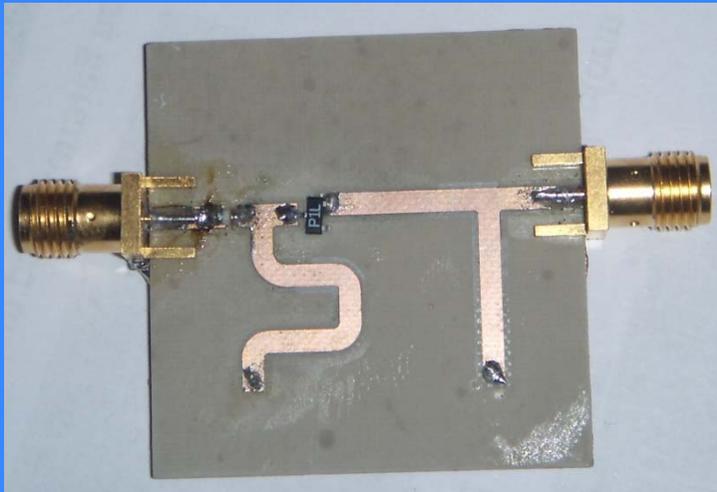
LeCroy SDA 100 GHz



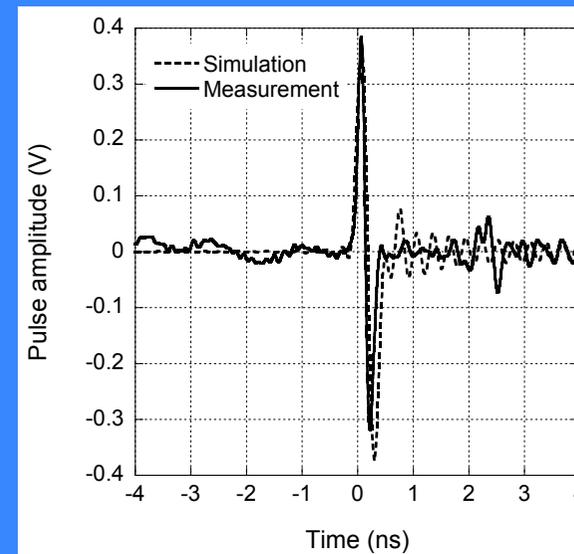
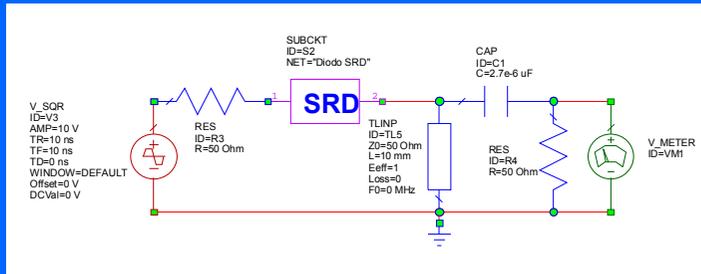
Impulso Gaussiano



Monociclo con linea in corto



Monociclo con C



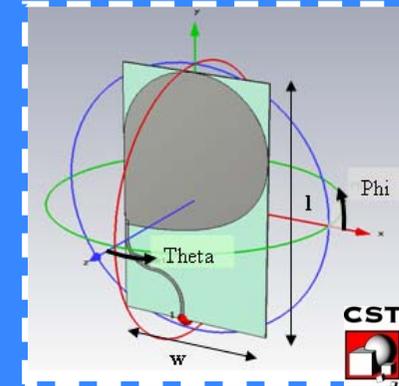
Progetto dell'antenna

Requisiti di una ANTENNA UWB:

- ✓ $S_{11dB} < -10 \text{ dB} \forall f \in \{3.1 \text{ GHz}, 10.6 \text{ GHz}\}$
- ✓ Dimensioni ridotte
- ✓ Tecnologie a basso costo
- ✓ Direttività $> 4 \text{ dBi}$

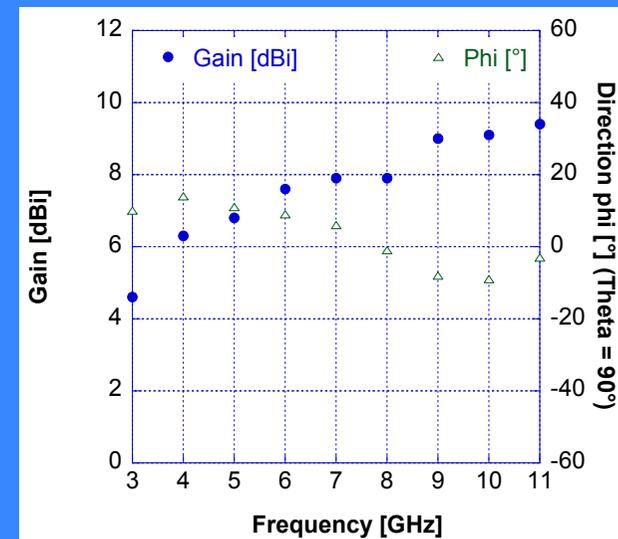
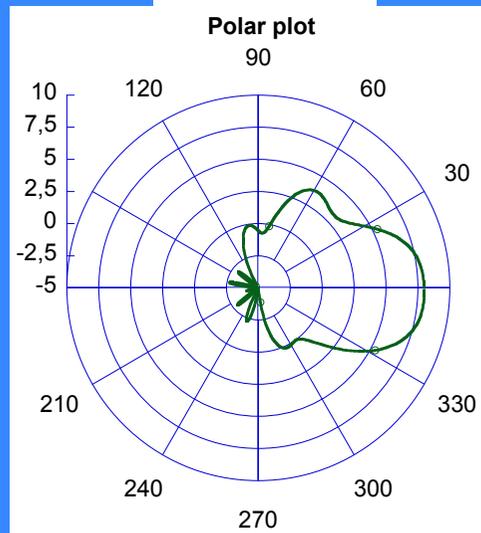
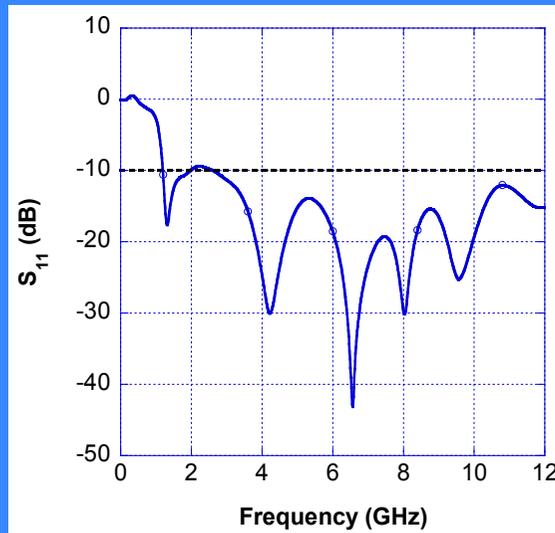
DIELECTRIC SUBSTRATE:

Rogers RO4003
 $\epsilon_r = 3.38$
 $h = 0.508 \text{ mm}$



$l = 75 \text{ mm}$
 $w = 50 \text{ mm}$

$f = 6 \text{ GHz}$



Fidelity

$$F = \max_{\tau} \frac{\int_{-\infty}^{+\infty} i_1(t) s_2(t + \tau) dt}{\sqrt{\int_{-\infty}^{+\infty} i_1^2(t) dt} \sqrt{\int_{-\infty}^{+\infty} s_2^2(t) dt}}$$

- $i_1(t)$ segnale ingresso
- $s_2(t)$ componente E_{θ} a distanza $d = 100$ mm dalla antenna per diverse direzioni

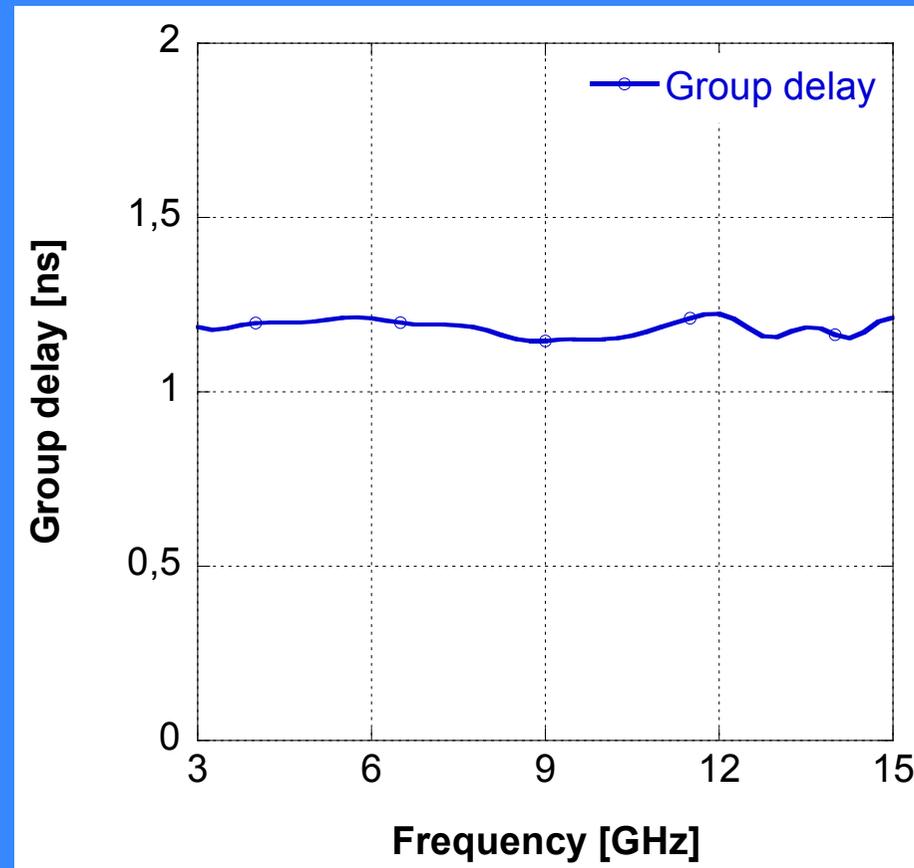
Probe position (xy plane)	Fidelity $i_1(t) = s_1(t)$	Fidelity $i_1(t) = ds_1(t)/dt$	Probe position (xz plane)	Fidelity $i_1(t) = s_1(t)$	Fidelity $i_1(t) = ds_1(t)/dt$
$\theta = 90^\circ \quad \varphi = 0^\circ$	0.947	0.983	$\varphi = 0^\circ \quad \theta = 0^\circ$	0.700	0.706
$\theta = 90^\circ \quad \varphi = 30^\circ$	0.961	0.964	$\varphi = 0^\circ \quad \theta = 30^\circ$	0.825	0.767
$\theta = 90^\circ \quad \varphi = 60^\circ$	0.964	0.975	$\varphi = 0^\circ \quad \theta = 60^\circ$	0.948	0.964
$\theta = 90^\circ \quad \varphi = 90^\circ$	0.925	0.928	$\varphi = 0^\circ \quad \theta = 90^\circ$	0.925	0.983

High Fidelity

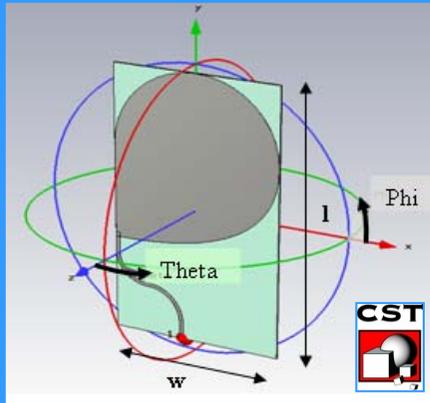
Ritardo di gruppo

$$u_g = -\frac{\partial \varphi(\omega)}{\partial \omega}$$

- $\varphi(\omega)$ risposta in fase



Realizzazione

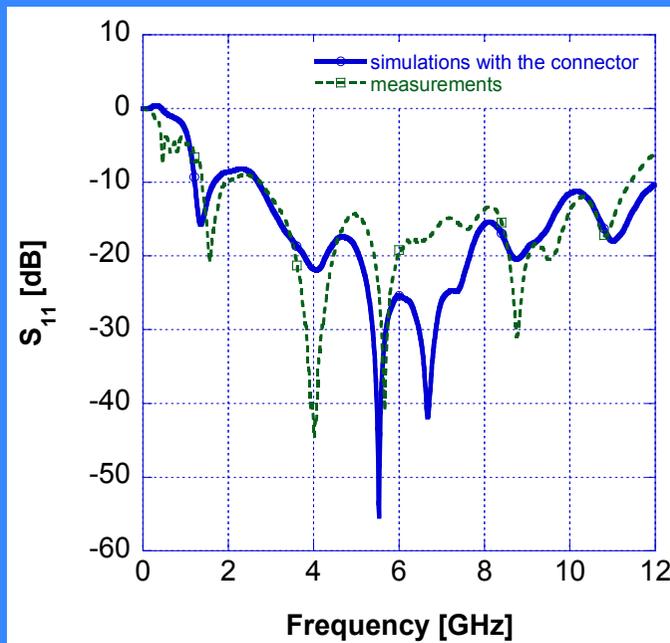


Substrato dielettrico

Rogers RO4003

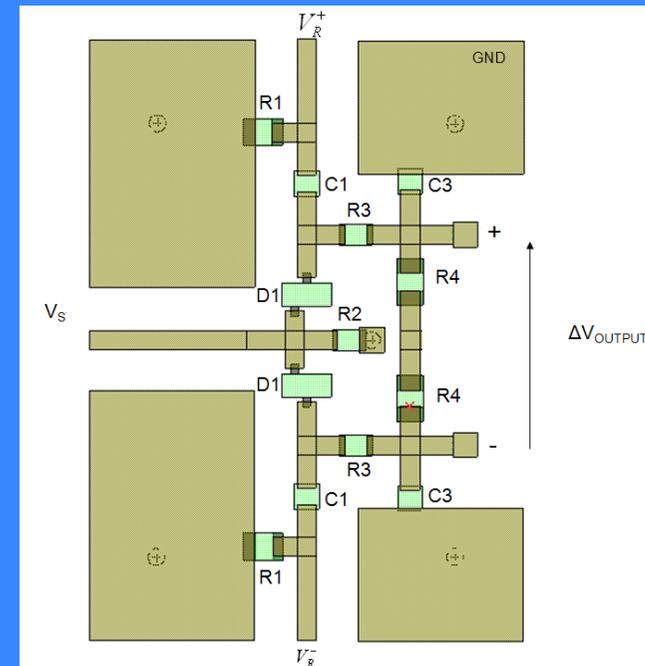
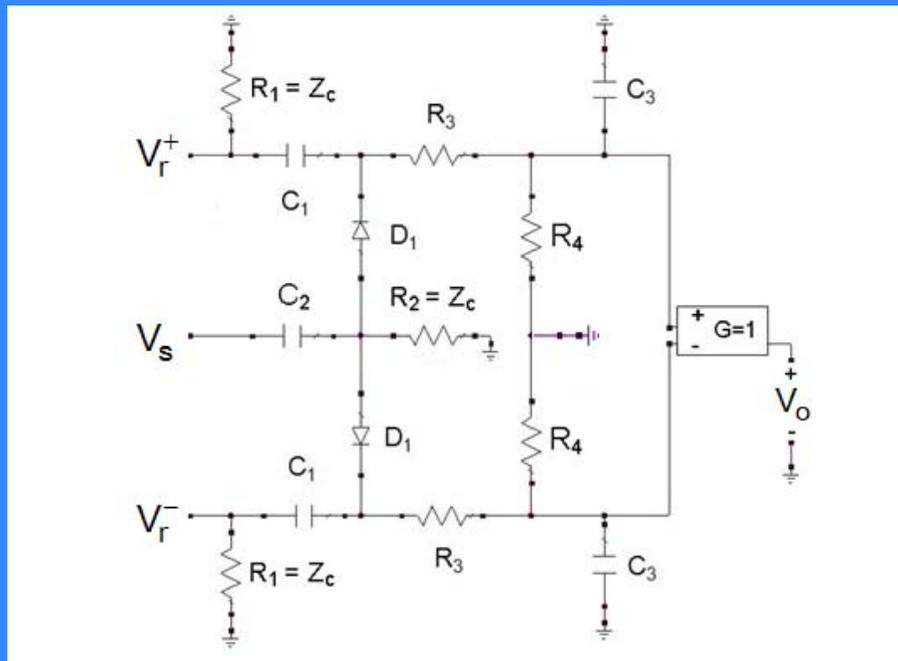
$$\epsilon_r = 3.38$$

$$h = 0.508 \text{ mm}$$

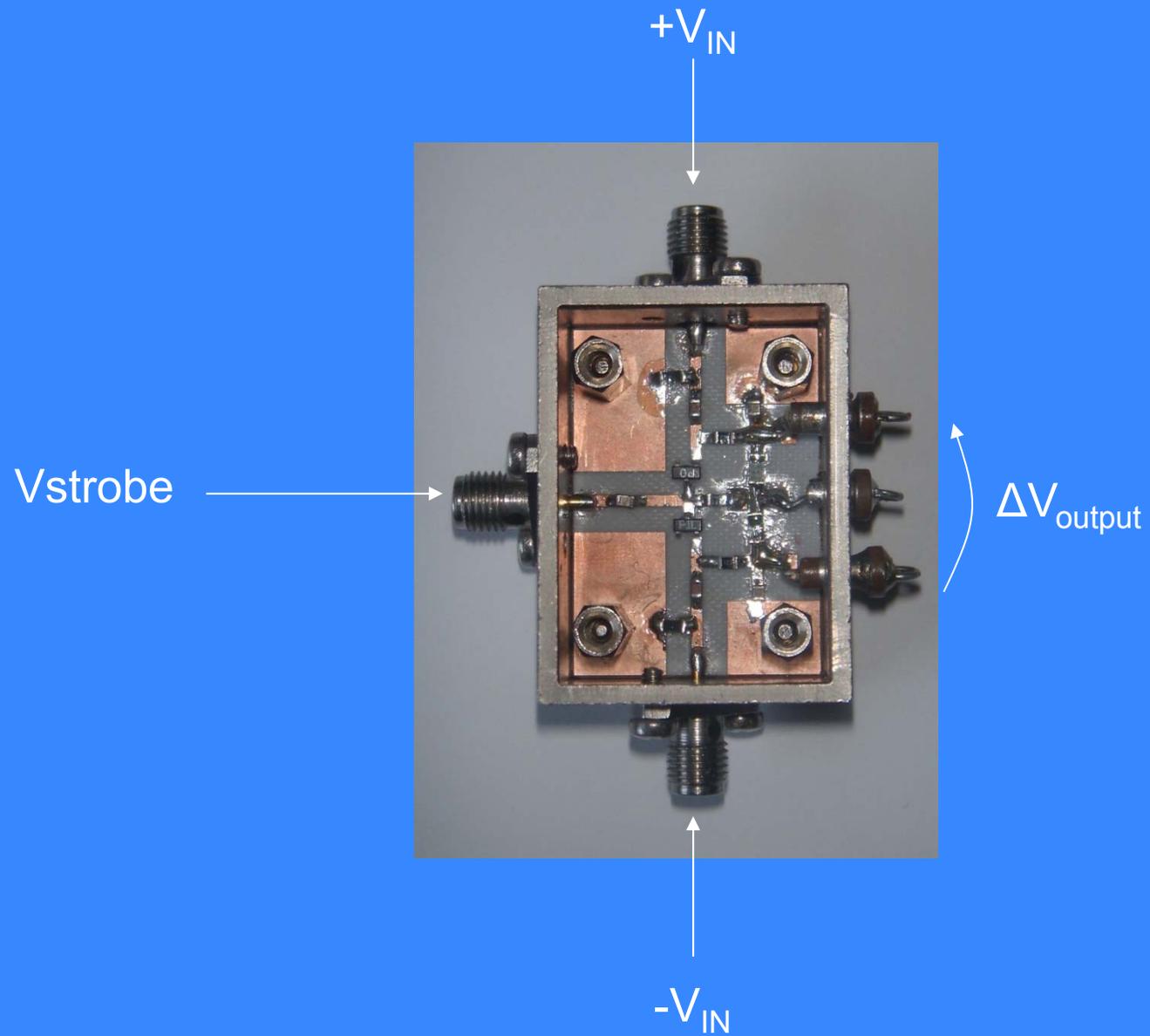


✓ **BUON ACCORDO TRA MISURE E SIMULAZIONI**

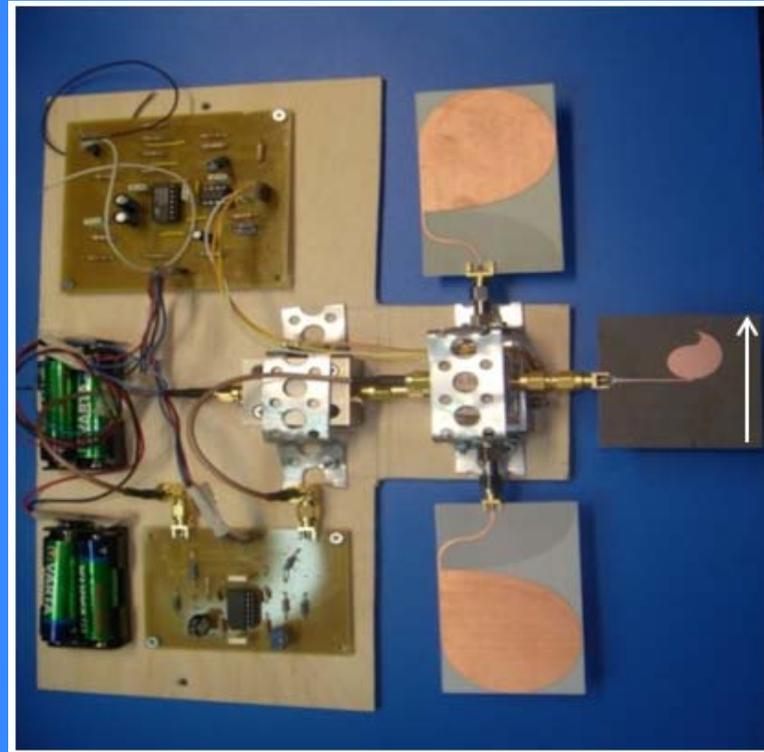
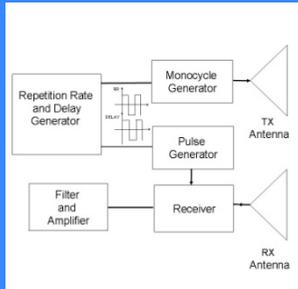
Progetto del ricevitore



Realizzazione ricevitore



Realizzazione del radar

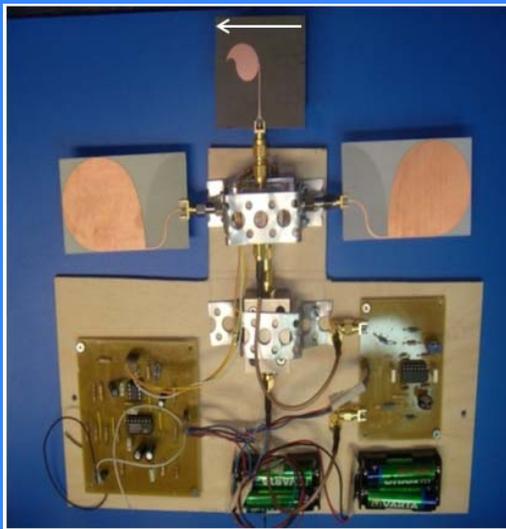


Assemblaggio dell'intero radar: il monociclo è inviato all'antenna trasmittente (a forma di goccia)

Il segnale viene ricevuto da due antenne speculari (a forma di mezzo cuore)

Test del radar: range e risoluzione

TARGET CHE SI MUOVE



E' stato preliminarmente studiata l'abilità del radar di discriminare piccoli movimenti usando una lastra di rame come target.

a) Lastra ferma: valor medio del rumore 0.58 mV;

b) Lastra a 40 cm dal radar: la lastra è stata spostata tra due punti la cui distanza è stata variata da 1 mm a 20 mm. In tutti i casi il radar è stato in grado di registrare le oscillazioni della lastra;

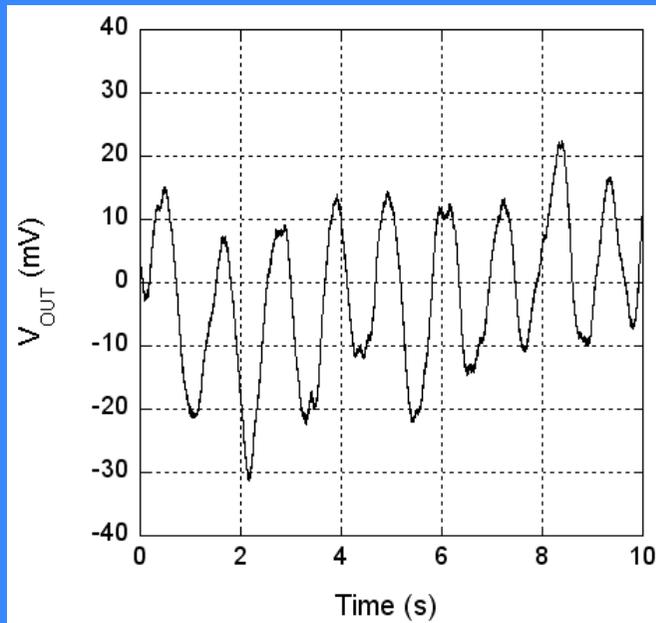
c) Lastra a 80 cm dal radar: la lastra è stata spostata tra due punti la cui distanza è stata variata da 1 mm a 20 mm. In tutti i casi il radar è stato in grado di registrare le oscillazioni della lastra.



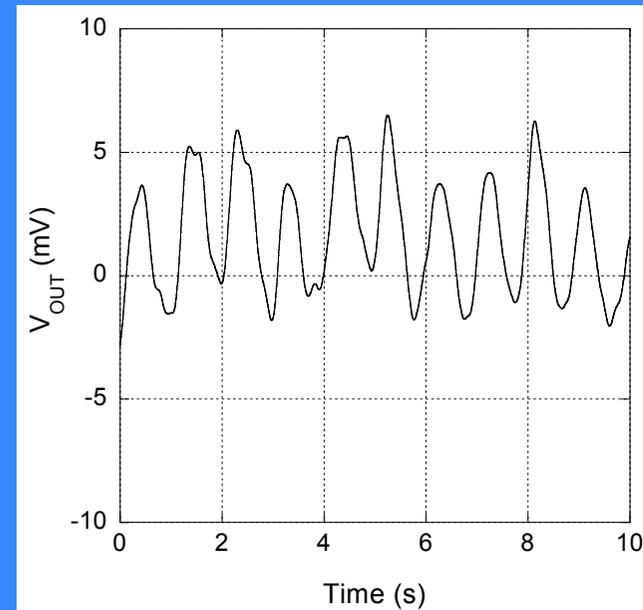
Range stimato = 100 cm

Risoluzione = 1mm/10

Tensione in uscita: oscillazioni 1 mm



distanza = 40 cm

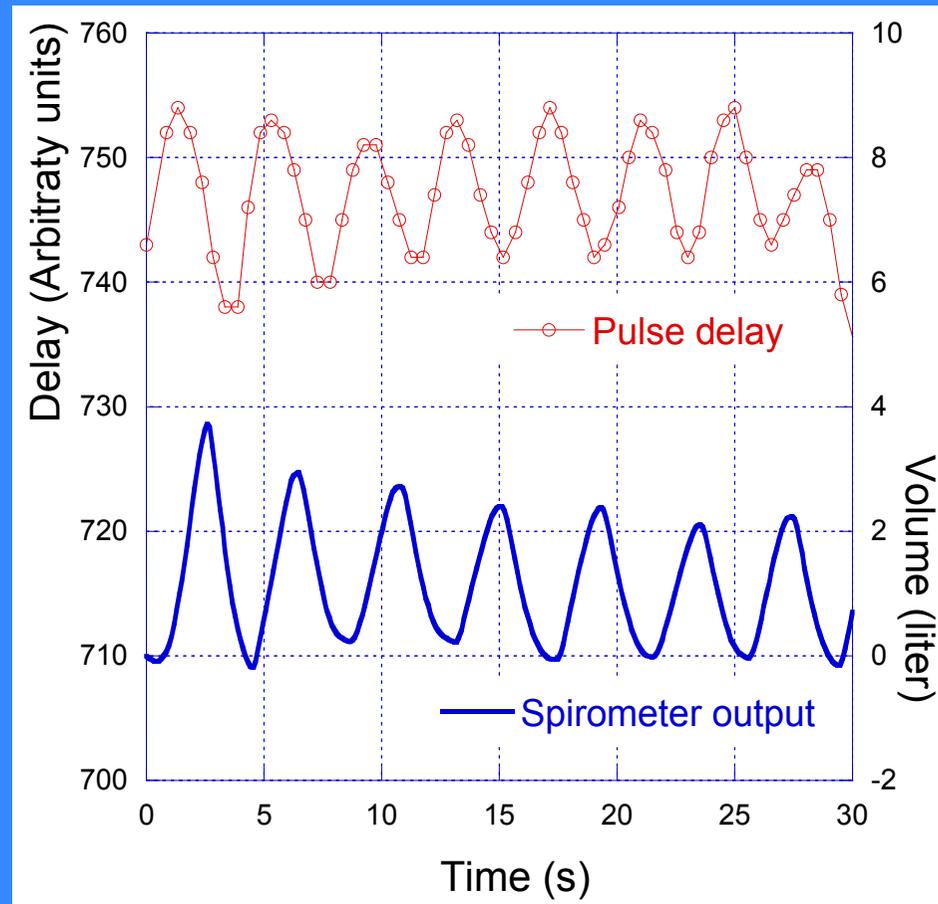


distanza = 80 cm

Confronto con lo spirometro



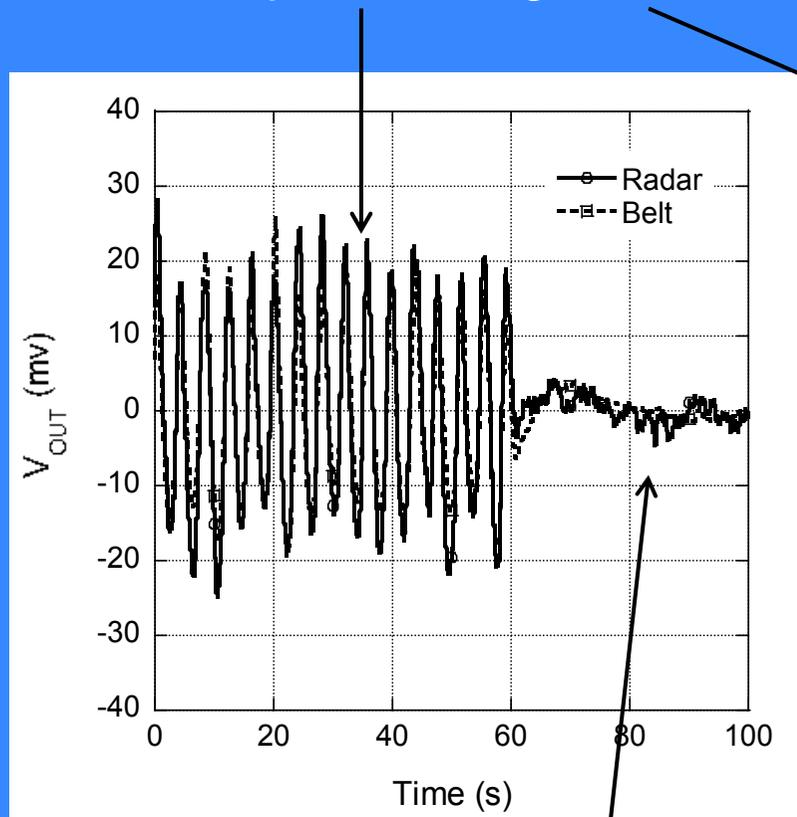
Andamento nel tempo del respiro nel tempo ottenuto con le **misure UWB** e con lo **spirometro**.



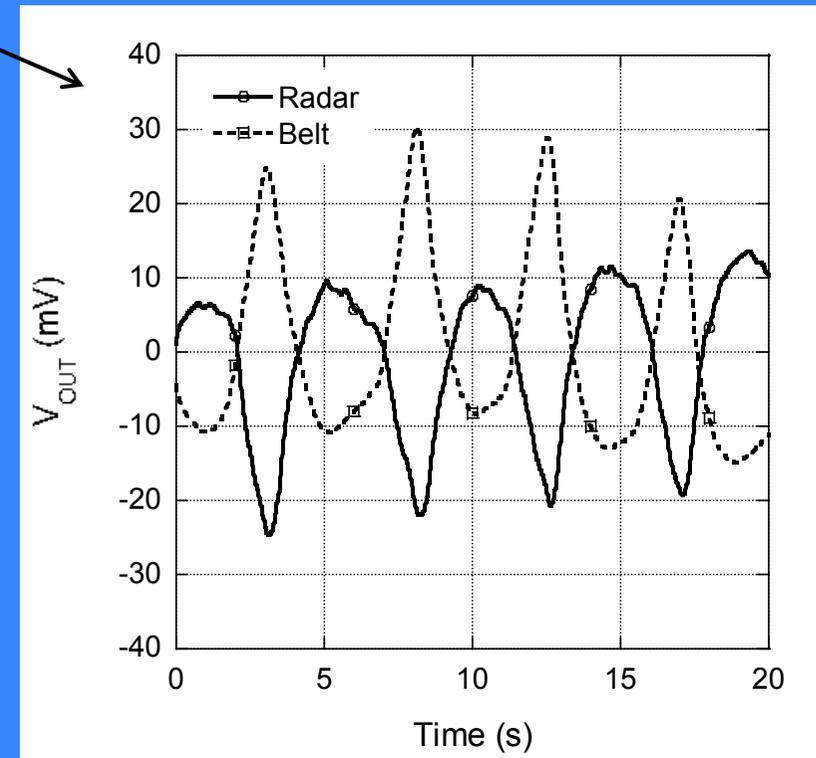
$f = 0.2562$ Hz dal segnale UWB
 $f = 0.2509$ Hz con lo spirometro

Confronto con le fasce piezoelettriche

Attività respiratoria regolare



Fase di apnea



Inversione di fase:

un ritardo dell'uscita ricevuta può dar luogo a un aumento o diminuzione del segnale di uscita del radar a seconda che lo strobe abbia un ritardo rispetto al segnale ricevuto maggiore o minore di zero, rispettivamente.

Salute dell'uomo

ICNIRP guideline (100 kHz – 10 GHz)

Popolazione

$SAR_{WB} < 0.08 \text{ W/kg}$ (corpo intero)

$SAR_{10g} < 2 \text{ W/kg}$ (testa e tronco)

$SAR_{10g} < 4 \text{ W/kg}$ (arti)

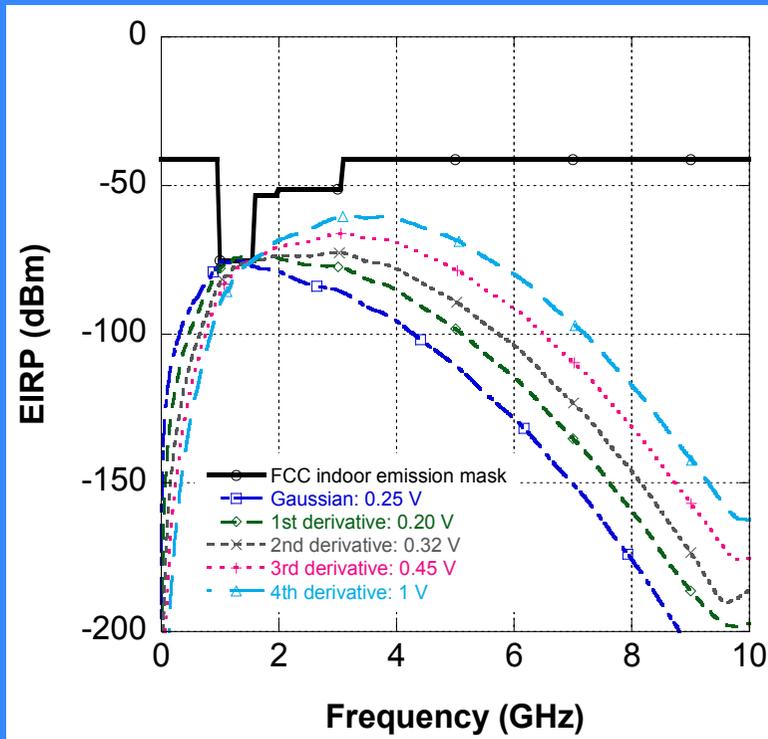
$E < 61 \text{ V/m}$

$H < 0.16 \text{ A/m}$

$PD < 10 \text{ W/m}^2$

Range di frequenza: 2 GHz to 300 GHz

Livelli espositivi in relazione alle maschere di emissione FCC



Simulazioni con il modello e l'antenna progettata

Sorgente: $f_{rip} = 1 \text{ MHz}$

$\sigma = 100 \text{ ps}$ (Gaussiane e sue derivate fino alla quarta)

EIRPmax = 1.76 μW

$E_{rms} = 0.007 \text{ V/m} \ll 61 \text{ V/m}$ (valore di riferimento ICNIRP)

Limiti di SAR in relazione alle maschere FCC

SAR valutato su un uomo di peso 72.4 kg

considerando tutta la potenza assorbita dal corpo:

$$SAR_{WB} = \frac{P_{RAD}}{M} = \frac{1.76 \mu W}{72.4 \text{ kg}} = 2.43 \cdot 10^{-8} \frac{W}{kg} \quad \ll 0.08 \text{ W/kg}$$

$$SAR_{10g} = \frac{P_{irr}}{M} = \frac{1.76 \mu W}{0.01 \text{ kg}} = 1.76 \cdot 10^{-4} \frac{W}{kg} \quad \ll 2 \text{ W/kg}$$

Valutazione SA (Specific Energy Absorption)

Calcolo SA (importante per tenere in conto eventuale esposizione della testa):
Partendo dal SAR_{10g} e essendo SA definita da:

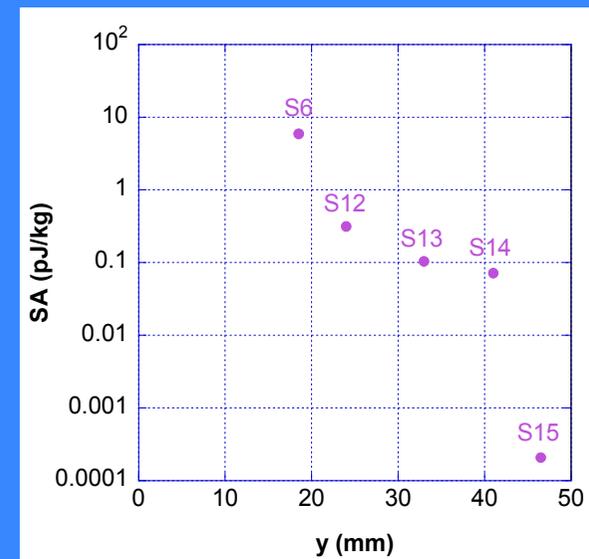
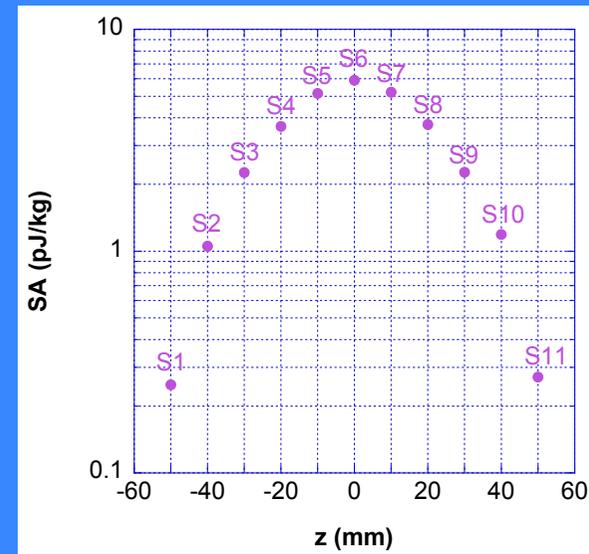
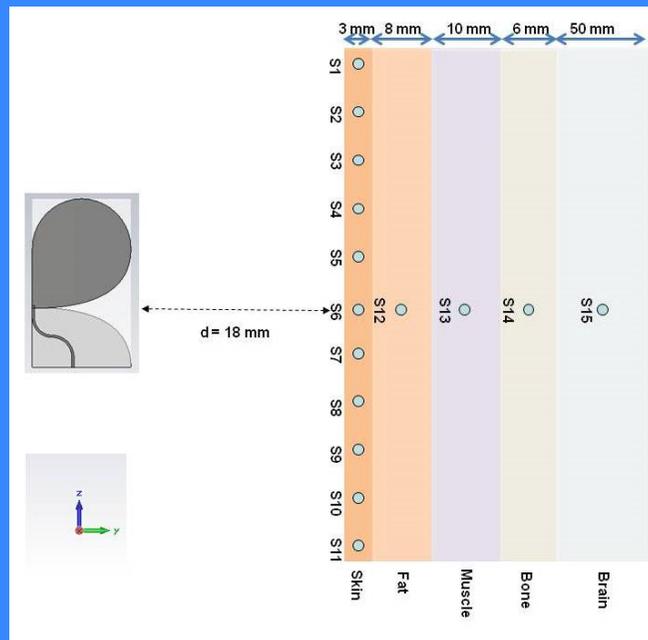
$$SA = \int_0^T SAR dt = SAR T$$

Per un periodo di $1 \mu s$
(corrispondente ad una frequenza di ripetizione di 1 MHz) si ottiene:

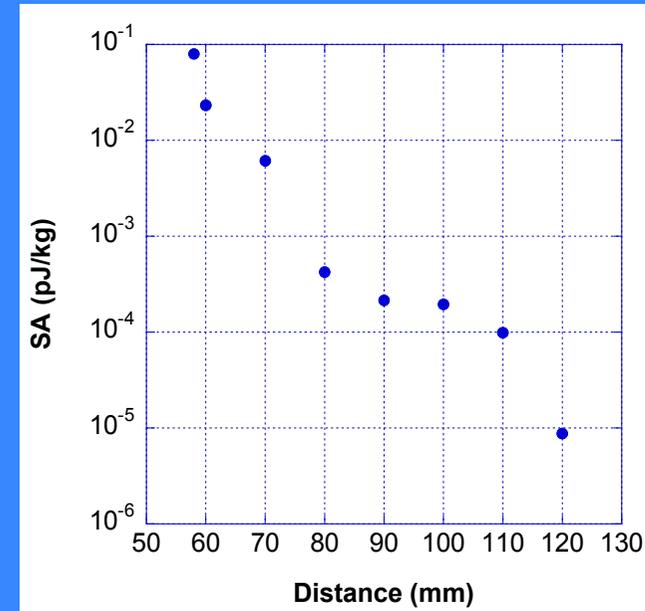
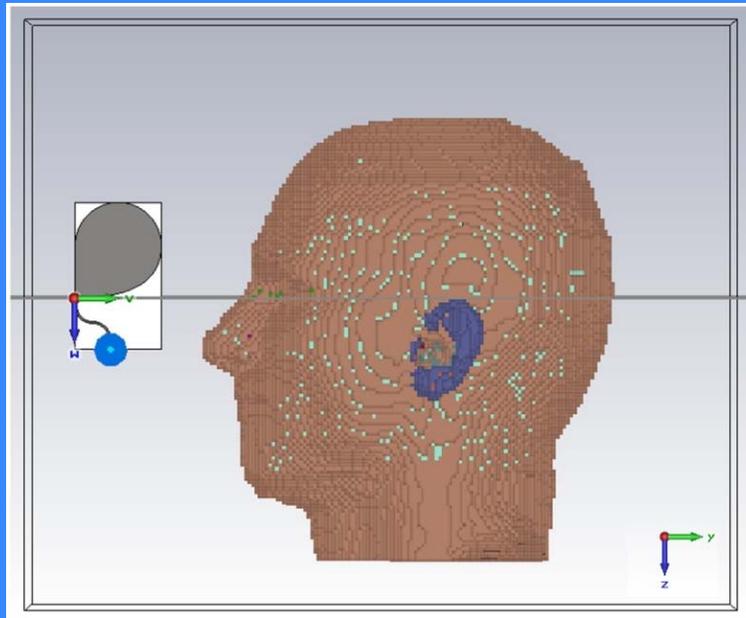
$$SA = 1.76 \cdot 10^{-4} \cdot 10^{-6} = 1.76 \cdot 10^{-10} \frac{J}{kg}$$

I valori di SA sono ben al di sotto dei limiti definiti dall'ICNIRP per la popolazione
(2 mJ/kg)

Valutazione di SA in un modello 3D della testa



Valutazione di SA in un modello anatomico 3D della testa



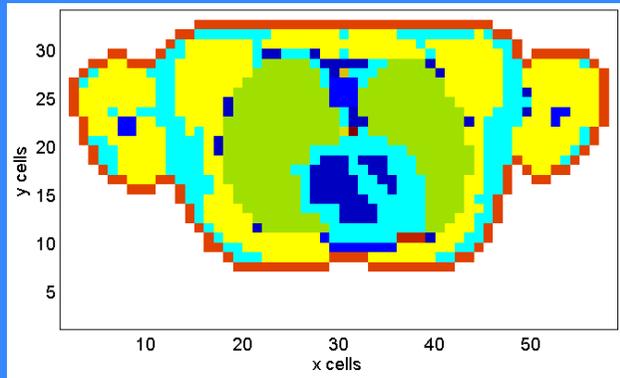
Il più alto valore di SA in corrispondenza della lente dell'occhio è

$$7.9 \cdot 10^{-2} \text{ pJ/kg} \ll 2 \text{ mJ/kg}$$

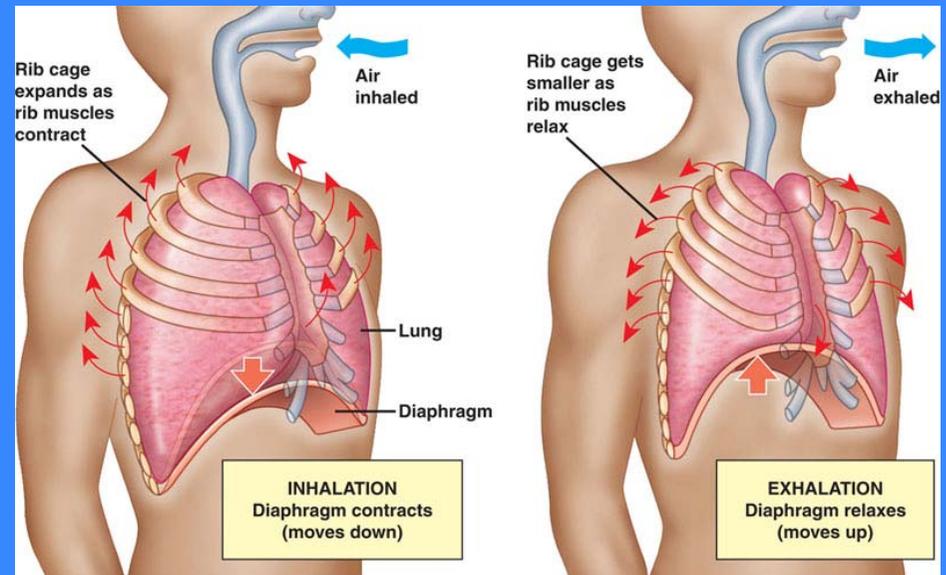
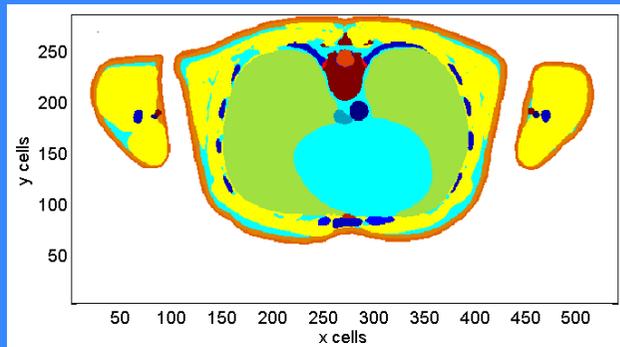
Sviluppo di modelli anatomici per studi di assorbimento e scattering

Sezioni trasversali

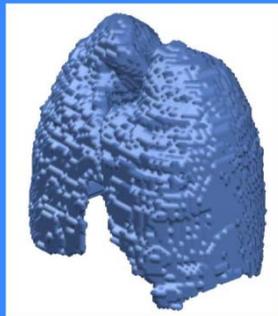
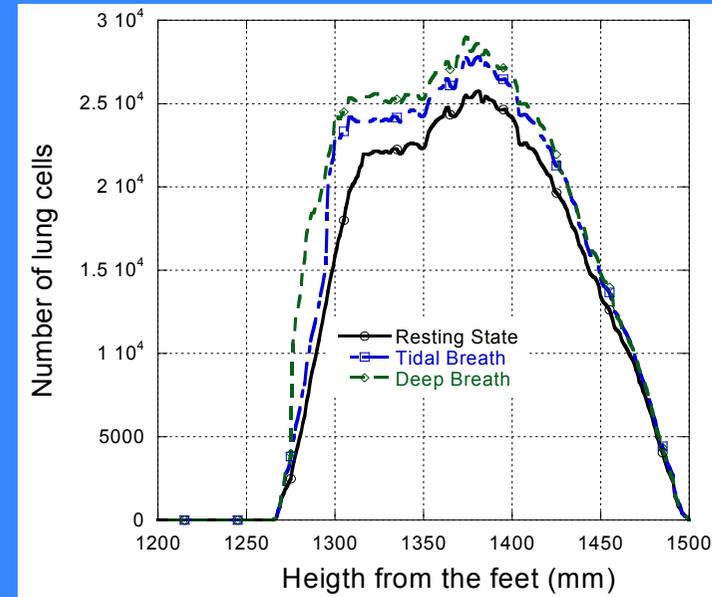
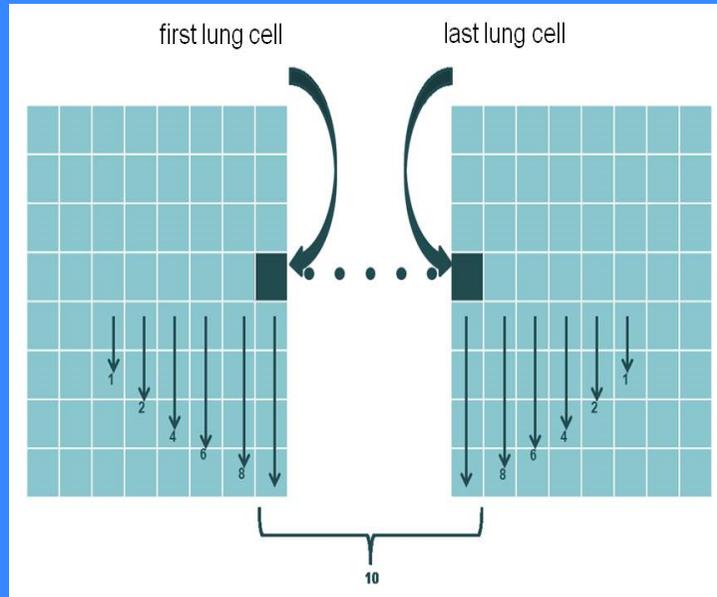
VH



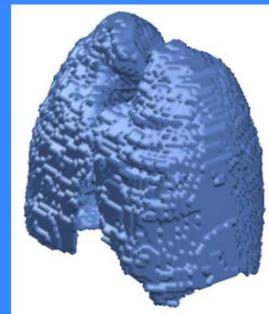
Duke



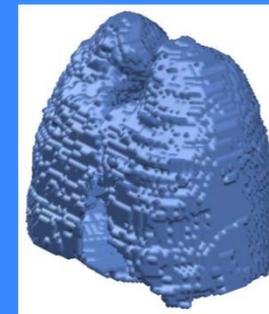
Modelli di respirazione tidale e profonda



Fine espirazione



Tidale



Profonda

Studi dosimetrici

I modelli ottenuti sono stati usati per studiare l'assorbimento di potenza quando esposti a un'onda piana a diverse frequenze nella banda UWB con una densità di potenza di 10 W/m^2

Sono stati valutati il SAR mediato sull'intero polmone, su 10 g e su 1 g di polmone

SAR mediato sull'intero tessuto polmonare

MODEL	3 GHz	4 GHz	5 GHz	6 GHz	7 GHz
RESTING	2.7310E-3	7.0364E-4	2.8091E-4	1.2376E-4	5.1650E-5
TIDAL	3.1763E-3	8.6341E-4	3.4483E-4	1.5667E-4	7.2919E-5
DEEP	4.004E-3	1.1832E-3	4.4893E-4	1.9865E-4	9.7269E-5

Questi modelli possono essere utilizzati per il calcolo della RCS di modelli anatomici "respiranti"

Studi dosimetrici

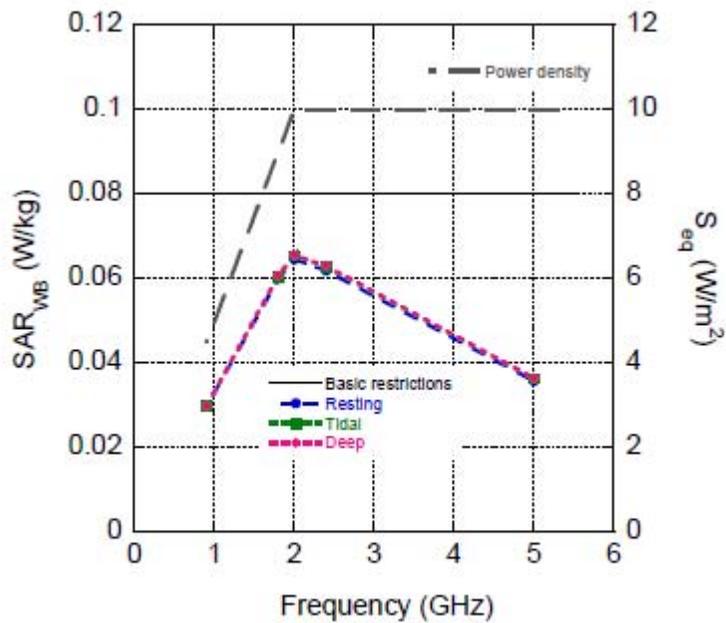


Figure 3. Whole body SAR for the RS, TB, and DB models for ICNIRP and IEEE-2005 reference levels.

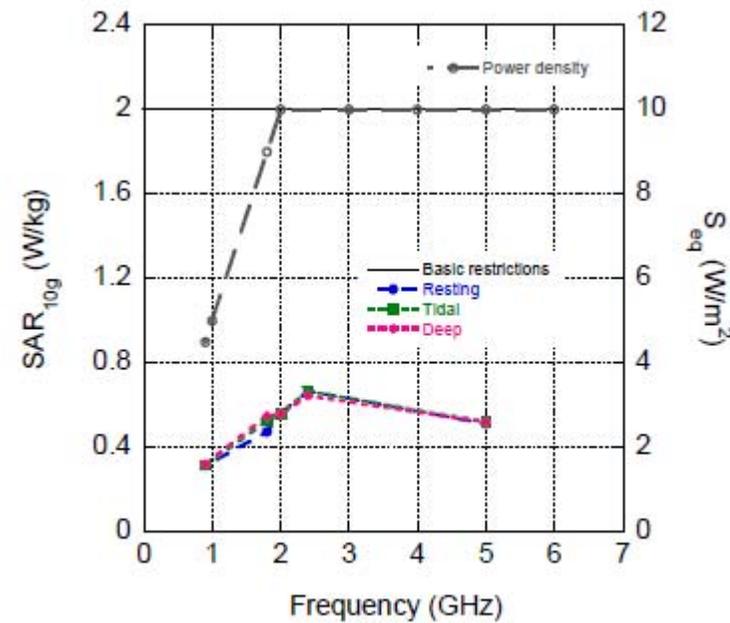
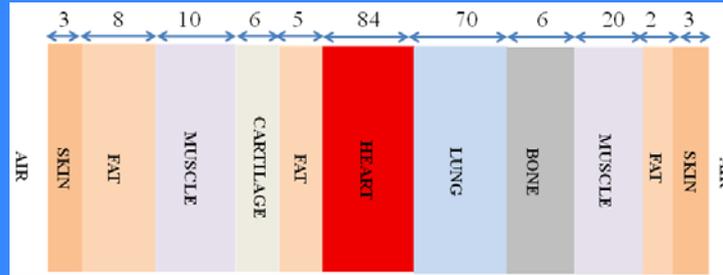


Figure 4. SAR_{10g} for the RS, TB, and DB models for ICNIRP and IEEE-2005 reference levels.

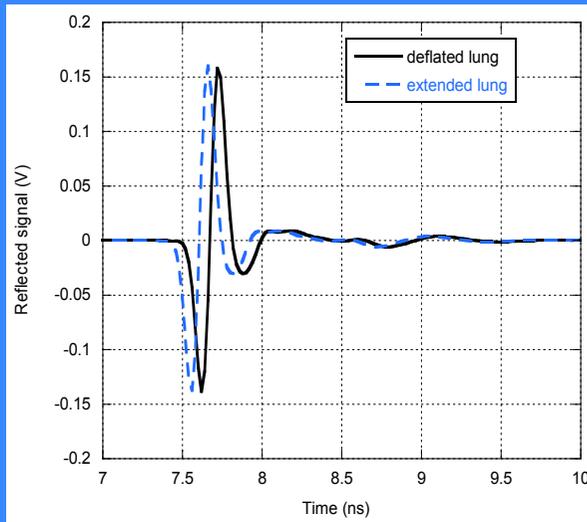


Interazione degli impulsi UWB con i tessuti umani: radar a 1 m

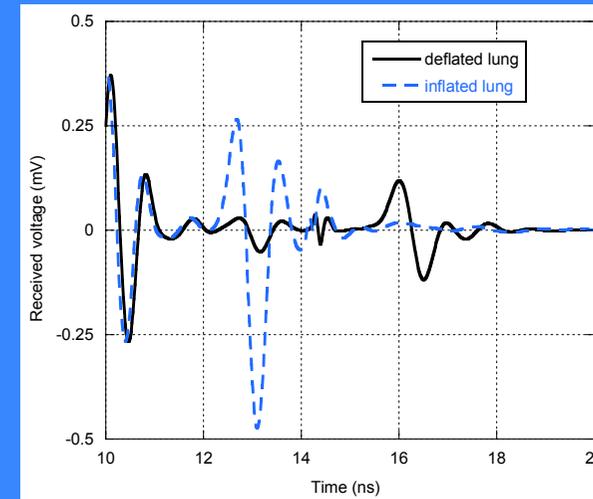
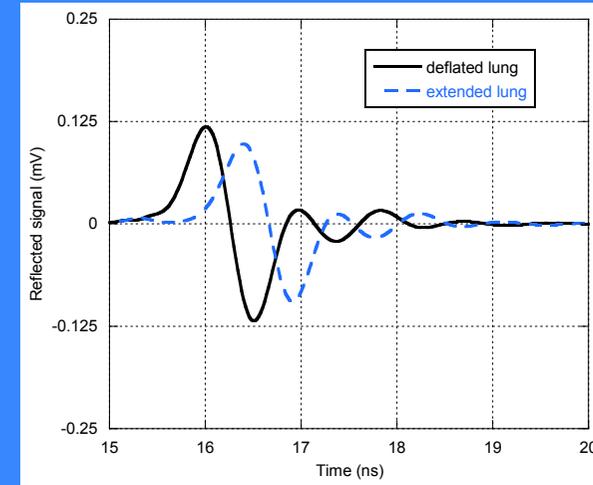


Duke:
34-years-old
1.77 m tall,
72.4 kg weight

Attività respiratoria



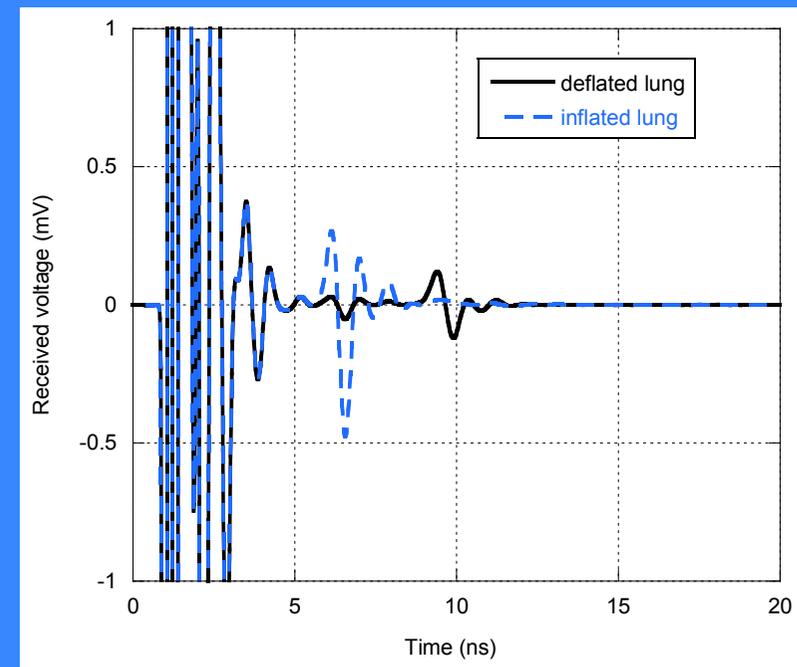
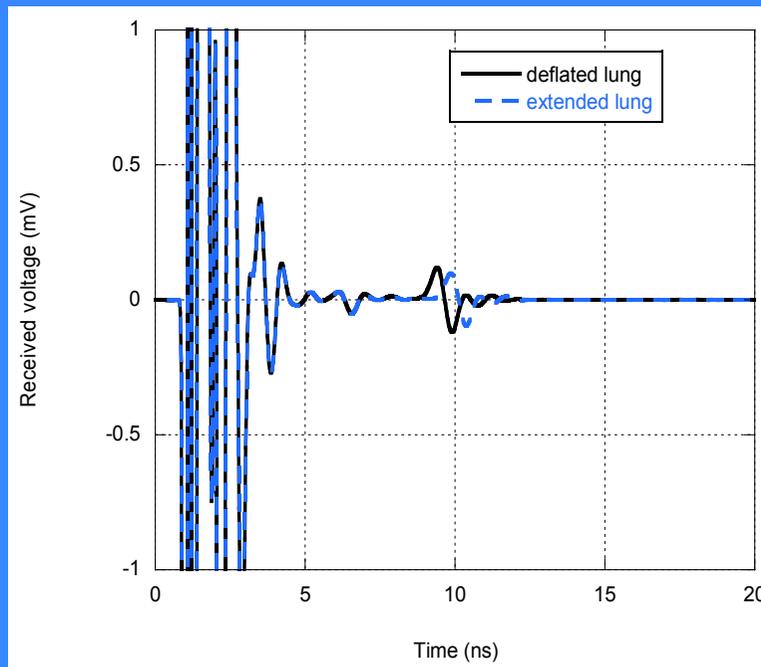
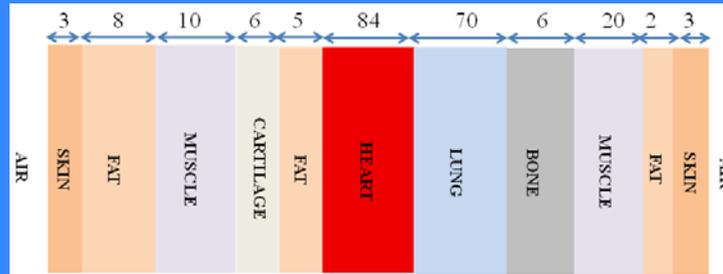
Riflessione pelle-aria



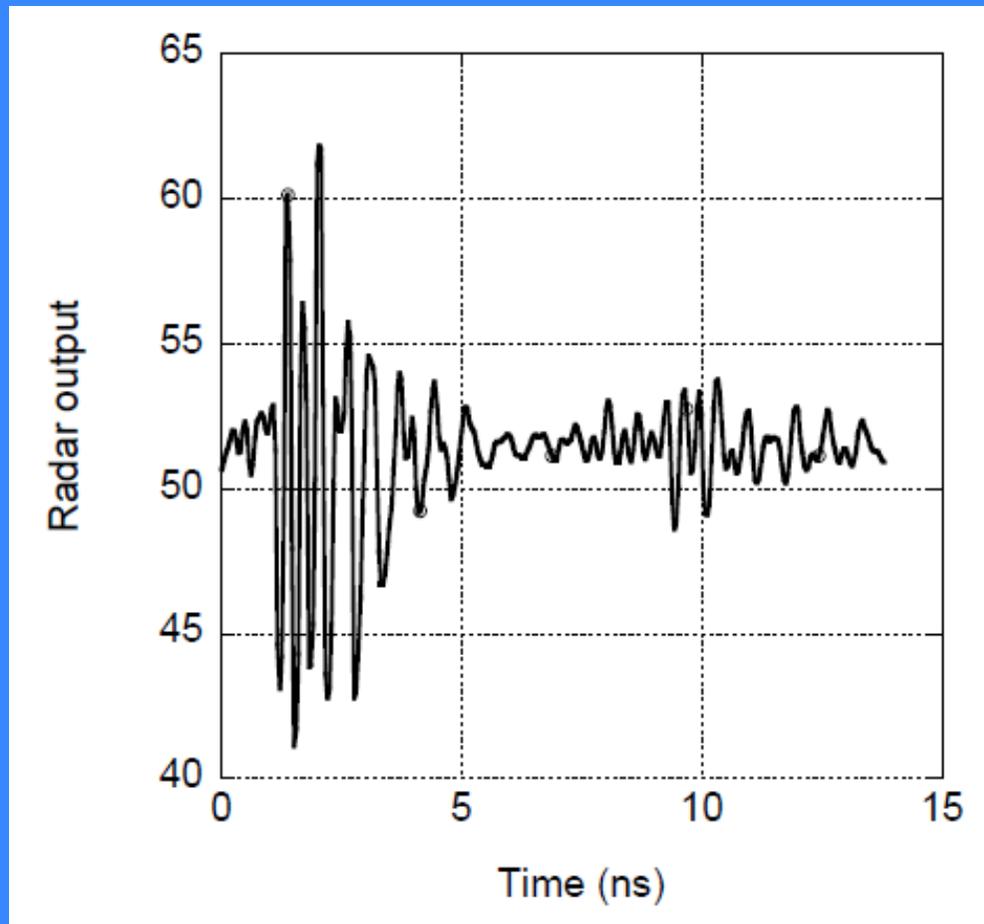
Riflessione strati interni



Interazione degli impulsi UWB con i tessuti umani: radar a contatto



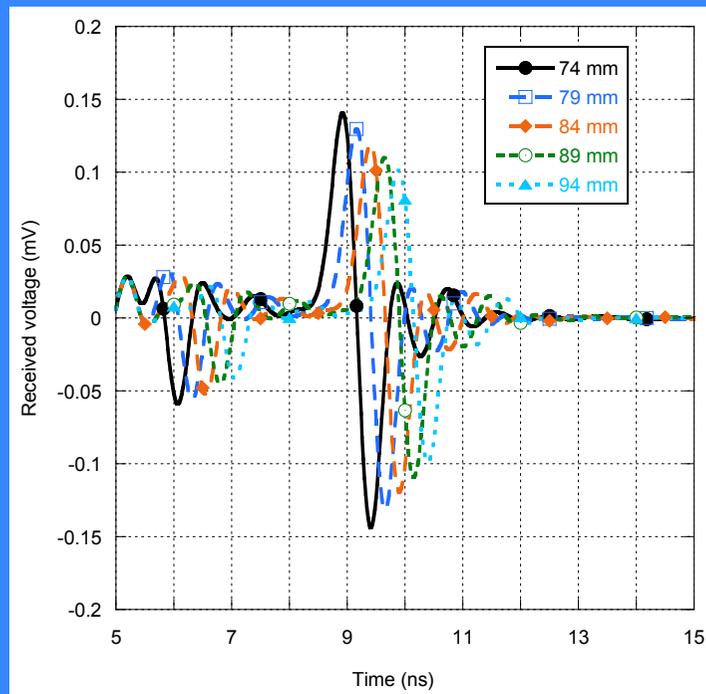
Misure: tensione ricevuta con il radar Novelda



CMOS impulse radar system used in the measurements is a radar integrated on a single chip, manufactured by Novelda (<https://www.novelda.no/>). The radar represents a sensor for human vital signs monitoring, personal security, environmental monitoring, industrial automation, and other novel sensor application.

Interazione degli impulsi UWB con i tessuti umani

Attività cardiaca



5 diverse lunghezze del muscolo cardiaco per simularne il battito:
le posizioni sono distinguibili andando a valutare il tempo di arrivo del picco del segnale ricevuto

Sviluppi Futuri

Hardware

- Migliorare il range del radar
- Ritardo variabile dell'impulso di strobe a controllo elettronico
- Miniaturizzazione del sistema

Software-Numerico

- Studio di nuovi modelli di uomo, anche donna e bambino per il calcolo della RCS per ottimizzare l'intero sistema
- Calcolo della RCS dell'uomo sfruttando i modelli anatomici sviluppati in modo automatico

Radar UWB per il monitoraggio remoto dell'attività respiratoria

Erika Pittella



SAPIENZA
UNIVERSITÀ DI ROMA