Investigating the Impact of Substrate Composition on 3D Printed mmWave CSRR Sensor

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COMSOL CONFERENCE
2020 NORTH AMERICA

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Study Overview

This study models a *3D printed* (3DP), mmWave, *complementary split ring resonator* (CSRR) sensor with varying *percentage infill* (I%) applied to the sensor's Nylon substrate. The sensor is intended for non-invasive *blood glucose measurement* (BGM). The *resultant relative permittivity* (ϵ_{eff}) of the sensor substrate was estimated using *mixture models* (MM). The predicted ϵ_{eff} were not in agreement, this produced a significant variation in the sensor model's performance. Results highlight the need for further work in identifying appropriate MMs for 3DP applications.

Background

- Noncommunicable diseases (NCDs) such as diabetes are a significant global socio-economic burden
- Constant blood glucose monitoring (BGM) is essential for diabetes care
- Non-invasive BGM provides superior patient comfort compared to BGM using blood samples (elderly and juveniles) [1]
- mmWave sensors are one method for non-invasive BGM [1]

Figure 1. **Traditional blood glucose meter in use (Credit: IDF Diabetes Atlas 2019 ED)**

Research Questions

What is the difference in the magnitude of the *resultant relative permittivity* (ϵ_{eff}) predicted by different heterogenous *mixture models* (MM)?

What are the magnitudes of the change in the CSRR sensor resonant frequency (f_r) and sensor S11 caused by the difference in the predicted ϵ_{eff}?

Study Details – CSRR Sensor

- For this study a complementary split ring resonator (CSRR) mmWave sensor is utilised [2]
- To reduce cost the CSRR sensor is intended to be produced using 3D printing (3DP)
  - Reduced weight by varying substrate percentage infill
  - Improved flexibility
  - Ability to easily customise

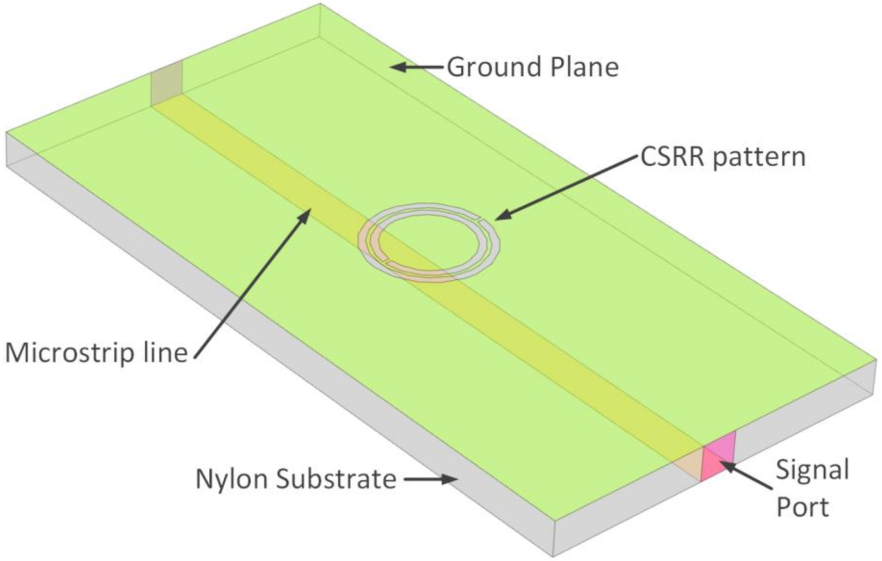


Figure 2. **Typical CSRR sensor structure**

Study Details – CSRR Sensor

- CSRR sensor uses the perturbation cavity method [2]
- Changes in sensor substrate ϵ_{eff} produce a resultant change in the sensor *resonant frequency* (f_r)

$$\boldsymbol{f_r = \frac{1}{2\pi\sqrt{Lr(Cc + Cr)}}}$$

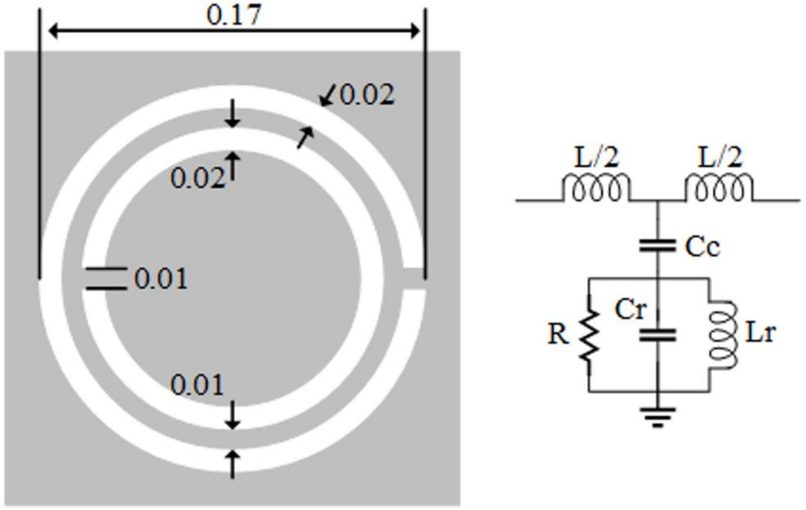


Figure 3. **mmWave CSRR dimensions (mm) and equivalent circuit**

Study Details – Mixture Models (MM)

- Varying I% for a 3DP substrate considered as a binary heterogenous mixture
- Mixture models predict the equivalent properties e.g. ϵ_{eff}
- Two MMs considered:
  - Landau & Lifshitz, Looyenga (LLL) [3]-[4]

$$\left(\epsilon_{eff}\right)^{1/3} = v_1\left(\epsilon_1\right)^{1/3} + v_2\left(\epsilon_2\right)^{1/3}$$

  - Rayleigh (RAY) [5]

$$\frac{\epsilon_{eff} - \epsilon_1}{\epsilon_{eff} + 2\epsilon_1} = v_2 \frac{\epsilon_2 - \epsilon_1}{2\epsilon_1 + \epsilon_2}$$

v_1, ϵ_1 volume, relative permittivity Nylon
v_2, ϵ_2 volume, relative permittivity Air

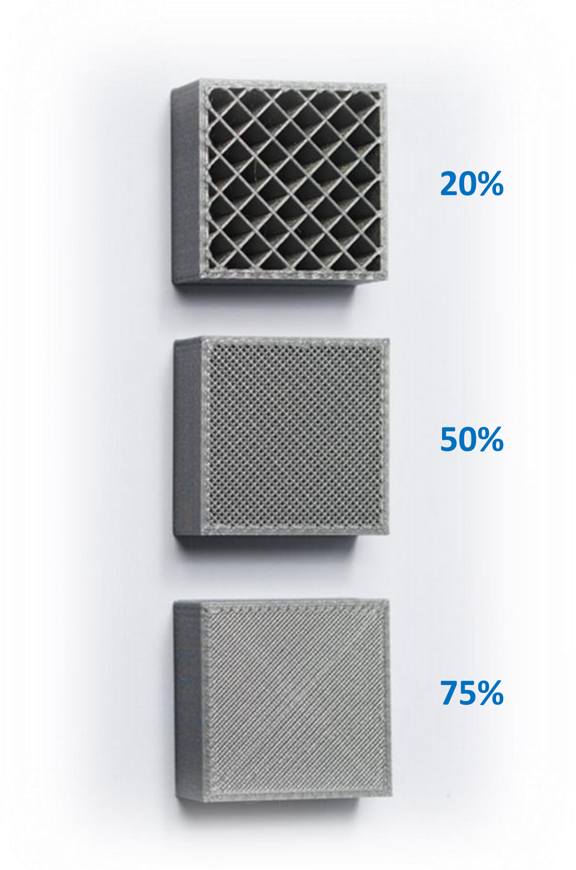
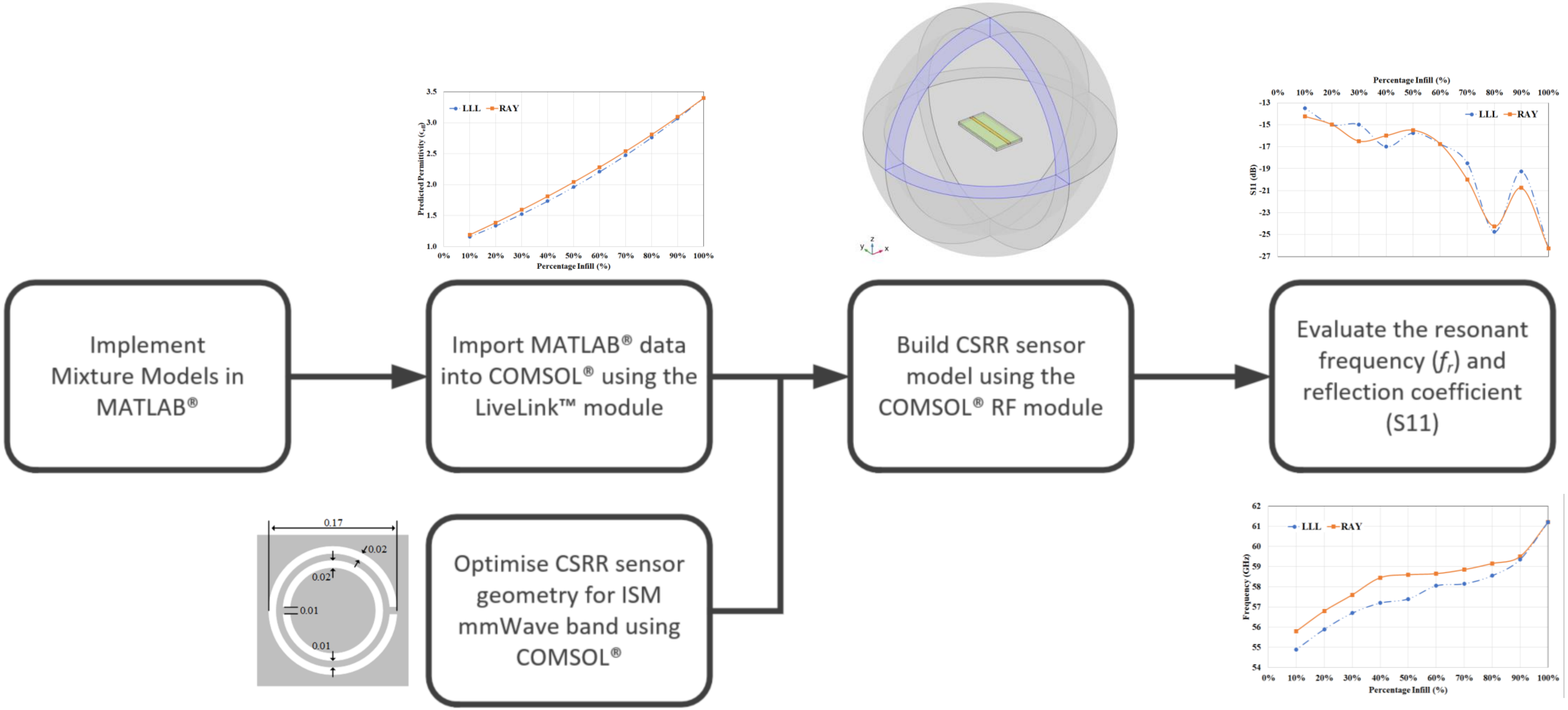


Figure 4. **Example rectangular I% (Credit: 3DHubs)**

Model Set-up



Implement Mixture Models in MATLAB®

Import MATLAB® data into COMSOL® using the LiveLink™ module

Build CSRR sensor model using the COMSOL® RF module

Evaluate the resonant frequency (f_r) and reflection coefficient (S11)

Optimise CSRR sensor geometry for ISM mmWave band using COMSOL®

Figure 5. **Workflow of the modelling process**

Model Set-up – Details

Item	Dimensions	Electrical Parameters
Microstrip	Trace width: 50 Ω impedance matched Trace length: 30.0mm	Perfect electric conductor
Substrate (Nylon)	15.0mm, 30.0mm, 0.8mm	σ = 10e-12 S/m ϵ_{eff} = set by mixture model calculation
Epidermis [6]	15.0mm, 30.0mm, 1.0mm	σ = 1.8e-2 S/m ϵ_r = 31
Air	Single layer sphere Layer thickness: 10mm Radius: 60mm	

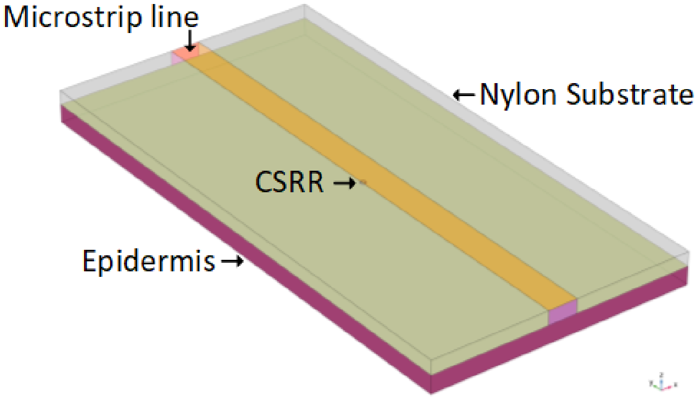


Figure 6. Details of the CSRR model with tissue

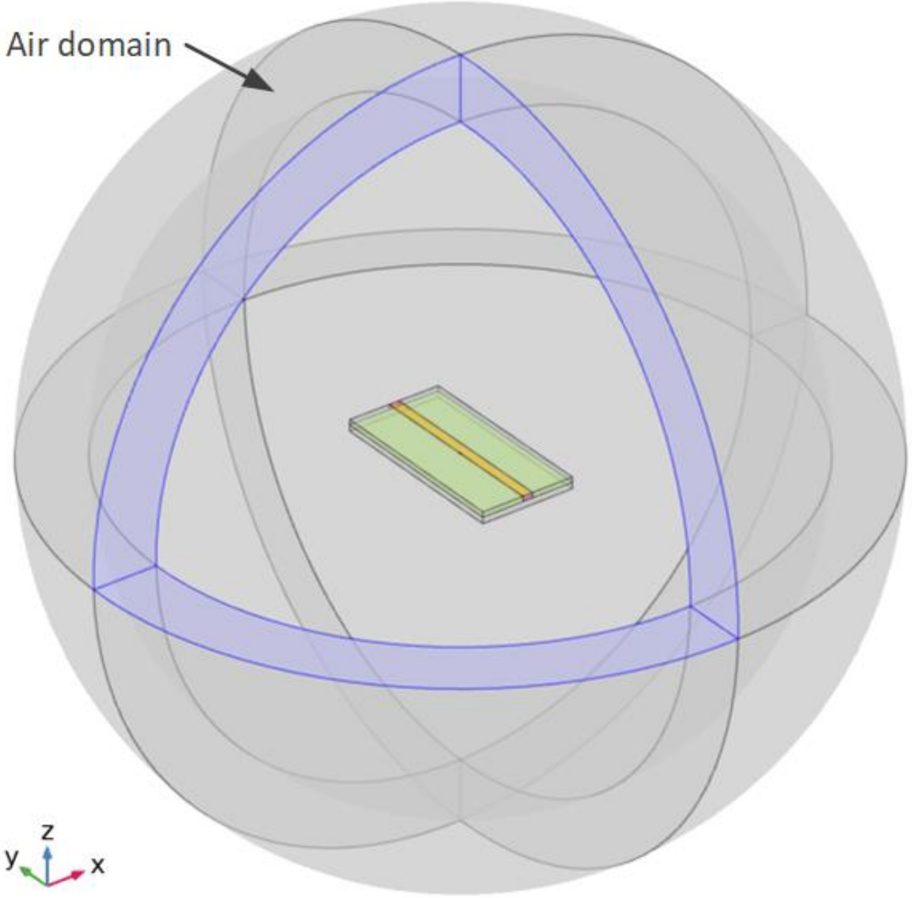
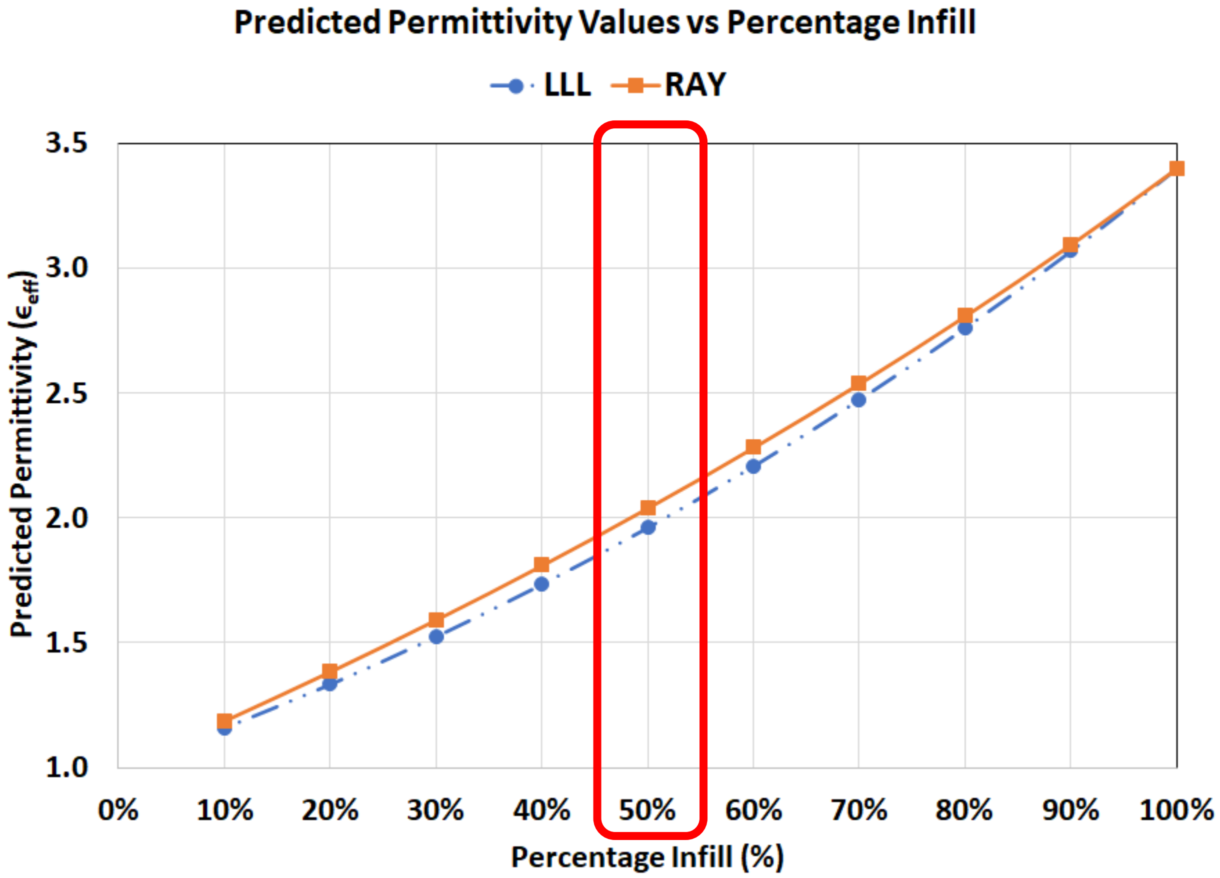


Figure 7. Full simulation model showing the air domain

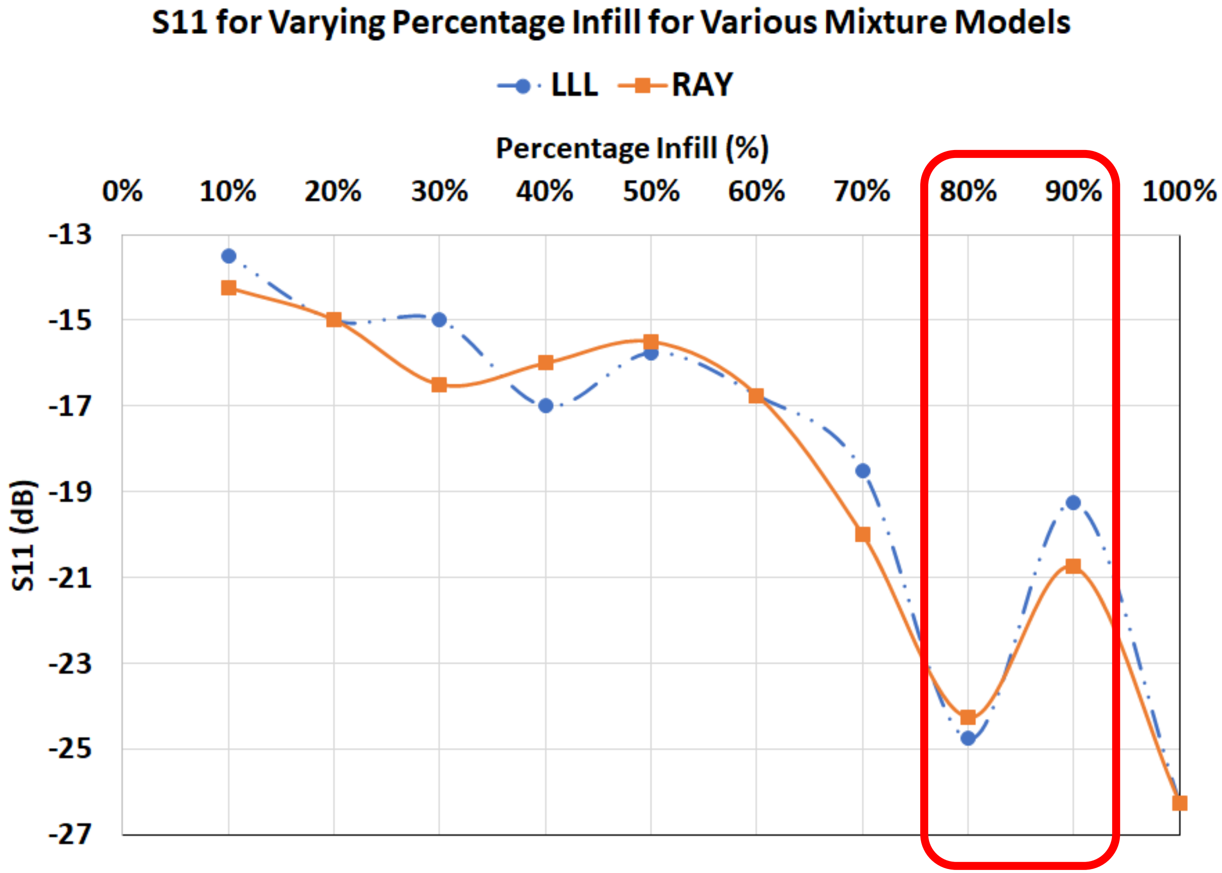
Results – Mixture Models

- The RAY mixture model generated higher values of ϵ_{eff} for all values of I%
- The greatest deviation between the two models was 0.08 at 50% I%



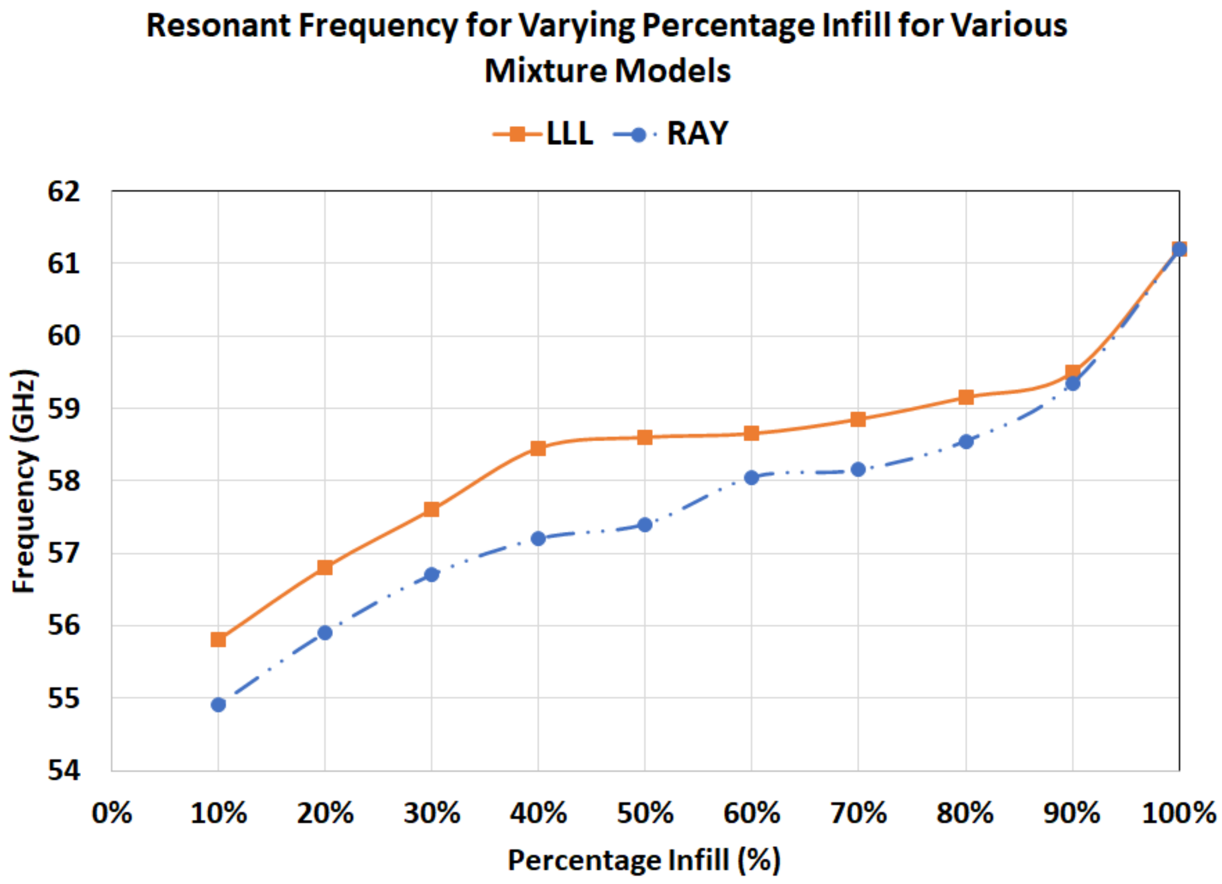
Results – Reflection Coefficient (S11)

- For both MMs, S11 decreased as I% was increased from 10%
- The trend in S11 was nonlinear
- $\Delta\epsilon_{eff}$ produced variations in ΔS11 (implementation margin)
- Overall, reduction in I% leads to increased mmWave reflection
- The greatest difference in predicted S11 was 1.5dB



Results – Resonant Frequency (f_r)

- For both MMs, f_r increased as I% was increased from 10%
- The trend in f_r was nonlinear
- Small $\Delta\epsilon_{eff}$ produced significant Δf_r
- The greatest difference in predicted f_r was 1.25GHz at 50% I%



Conclusion

- The CSRR sensor responds to variations in the ϵ_{eff} of the patient's tissue caused by changes in glucose concentration
- $\Delta\epsilon_{eff}$ produce a resultant Δf_r (in the order of GHz) for the CSRR sensor
- The variations in the MMs predictions for ϵ_{eff} can translate into significant errors in the manufactured sensor measurement of patient glucose
- Appropriate MMs for 3DP need to be identified
  - Build and test a significant number of 3DP samples
  - Further investigation of substrate tuning

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