A 2.4 GHz FREQUENCY SELECTIVE BACKSCATTER MODULATOR FOR BLUETOOTH AND WI-FI BACKSCATTER

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Background and Motivation

- Backscatter devices used in many Internet of Things (IoT) applications[1-4]
- Adoption of ultra-low power backscatter modulators (**BSMs**) has potential to dramatically reduce creation of hazardous battery waste
- **Open problem**: a single BSM scatters energy from all nearby sources in the environment → leads to spectral pollution and potential for interference with other nearby communication links
- **Our approach**: add in-line band-pass filter (BPF) to create a **frequency selective (FS) BSM**, which preferentially modulates signals within BPF's passband, regardless of antenna's bandwidth (BW)
- In Bluetooth (BT) or Wi-Fi context, our approach could allow backscatter within only the 2.4 GHz ISM band, or ideally within 20 MHz bandwidth of a single Wi-Fi channel

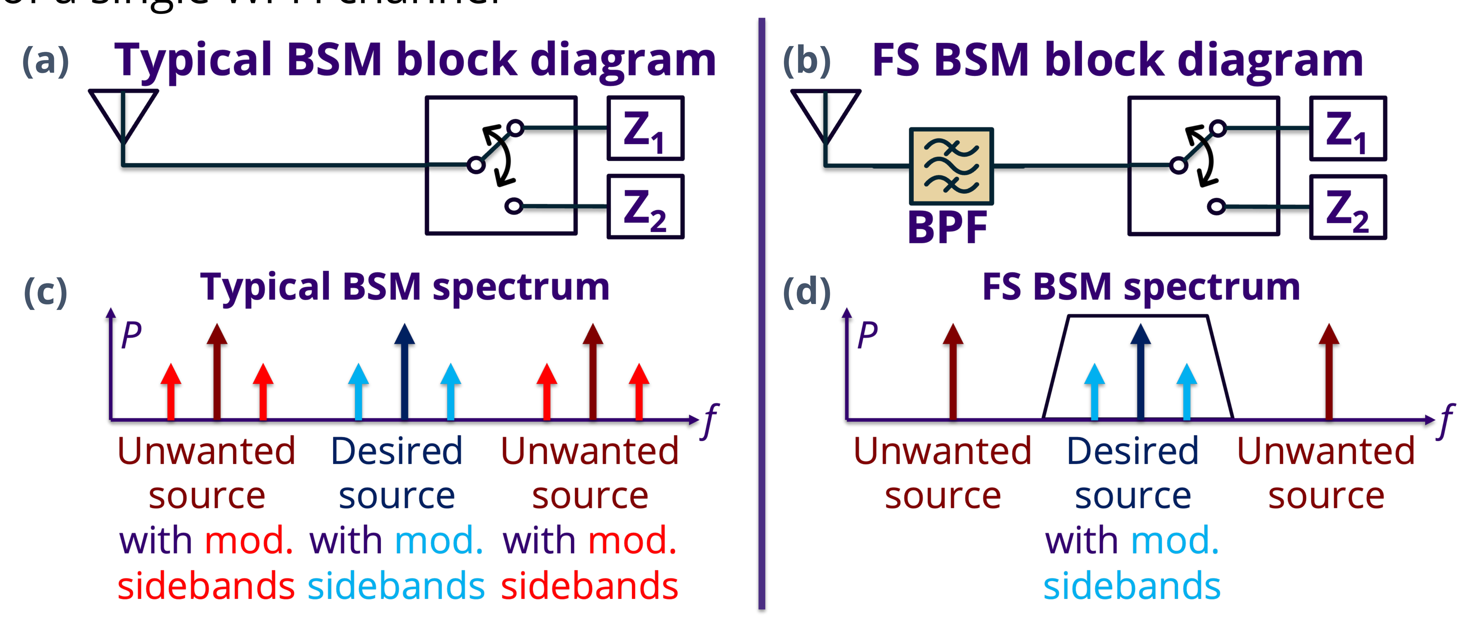
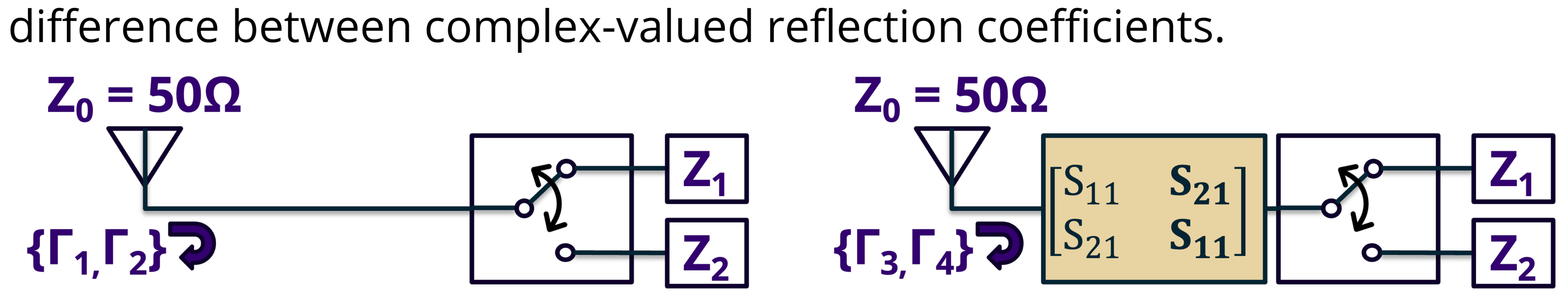


Fig. 1: Block diagram of (a) a typical BSM and (b) the proposed FS BSM. Spectrum of (c) a typical BSM, including unwanted backscatter modulation of out-of-band carriers, and (d) the proposed FS BSM. The addition of a BPF ensures scattering from carriers in the desired band.

Engineering Frequency Selectivity

The frequency-dependent **differential reflection coefficient**, $|\Delta\Gamma|$, is used to characterize amount of modulated backscatter. $|\Delta\Gamma|$ ranges from 0 to 2 for minimum to maximum backscatter and is computed as the difference between complex-valued reflection coefficients.

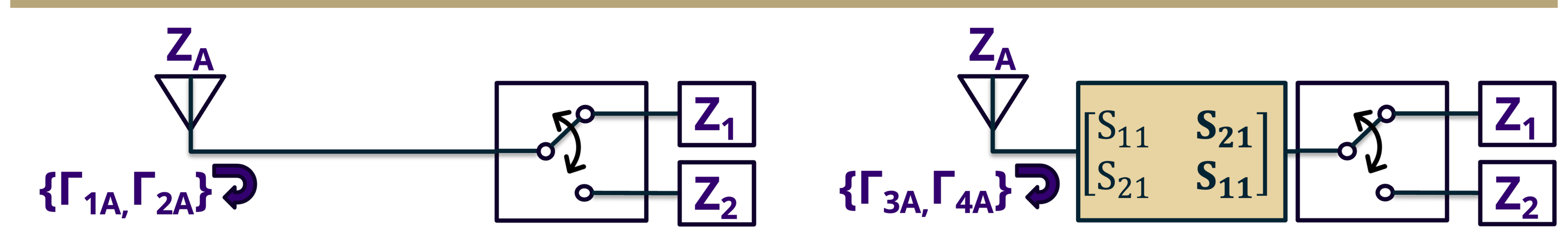


$$|\Delta\Gamma_{M,50\Omega}| = |\Gamma_1 - \Gamma_2|$$

$$|\Delta\Gamma_{F,50\Omega}| = \frac{|S_{21}|^2 |\Delta\Gamma_{M,50\Omega}|}{|(1 - S_{11}\Gamma_1)(1 - S_{11}\Gamma_2)|}$$

- Adding reciprocal 2-port network yields a new, **filtered** $|\Delta\Gamma_{50\Omega}|$, which is a scaled version of the original
- An ideal BPF enables **frequency selective** $|\Delta\Gamma_{F,50\Omega}|$.
  →**Stopband**: $|S_{11}| = 1$ and $|S_{21}| = 0 \rightarrow |\Delta\Gamma_{F,50\Omega}| = 0$.
  →**Passband**: $|S_{11}| = 0$ and $|S_{21}| = 1 \rightarrow |\Delta\Gamma_{F,50\Omega}| = |\Delta\Gamma_{M,50\Omega}|$

Practical Considerations



$$|\Delta\Gamma_{M,A}| = |\Gamma_{1A} - \Gamma_{2A}|$$

$$|\Delta\Gamma_{F,A}| = |S_{21}|^2 \left|\frac{f(\cdot)}{g(\cdot)}\right| |\Delta\Gamma_{M,A}|$$

- In practice, an antenna having complex impedance $\mathbf{Z_A} \neq \mathbf{50\Omega}$ is used
- After converting each 50Ω-ref'd Γ_n into its respective impedance parameter, Z_n, the corresponding reflection coefficient seen by the antenna is found as: $\mathbf{\Gamma_{nA}} = \frac{Z_n - Z_A^*}{Z_n + Z_A}, \mathbf{n} \in \{\mathbf{1,2,3,4}\}$

Crucially, an ideal BPF can also **enable frequency selective** $|\Delta\Gamma_{F,A}|$

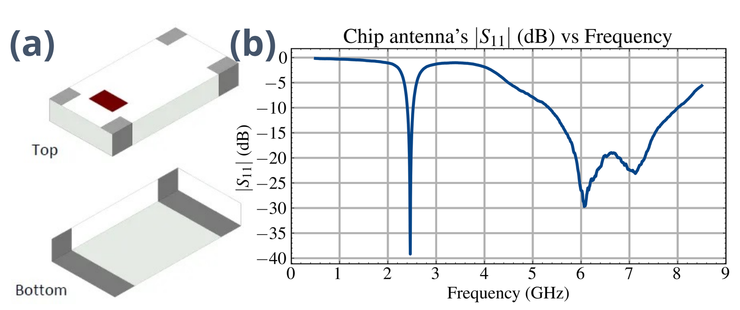


Fig. 2: (a) diagram and (b) $|S_{11}|$ of antenna

Considered generic chip antenna from Johanson Inc. for $|\Delta\Gamma_A|$

- Good for BT and Wi-Fi applications w/ primary 2.4–2.5 GHz passband
- Additional passbands around 5 and 6 GHz

Experimental Validation

All three devices evaluated are commonly used in backscatter applications[5] and compatible with 0-5V logic levels of Arduino Nano microcontroller:

1. **Varactor:** voltage tunes Cap. from 36 pF to 2.7 pF
2. **PIN diode:** open- or short-circuit when rev. or fwd. biased
3. **pHEMT:** open- or short-circuit as gate driven low or high

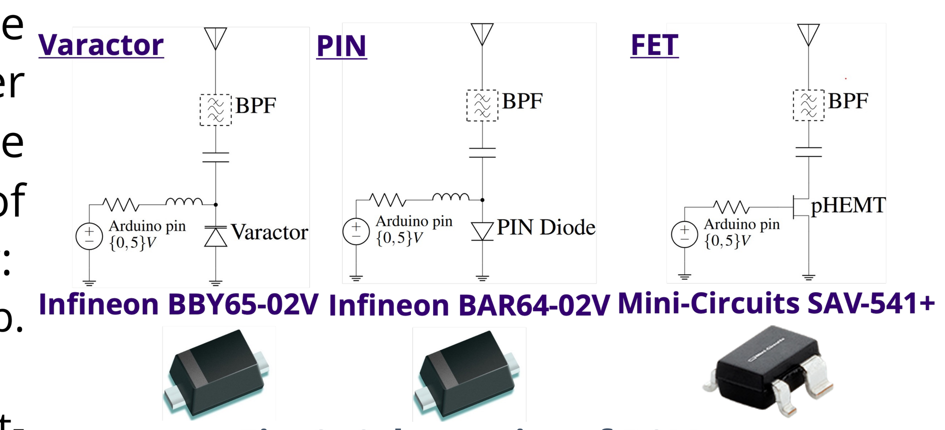


Fig. 3: Schematics of BSMs

Paired with two filter types:

1. Off-the-shelf low-temperature co-fired ceramic (**LTCC**) BPF
2. Microstrip custom filter (**CF**) = Stepped-impedance low-pass filter (LPF) + microstrip coupled line BPF (MCFIL)

Designed and fabricated FR-4 printed circuit board (PCB) for microstrip CF, and three FR-4 PCBs for the modulators.

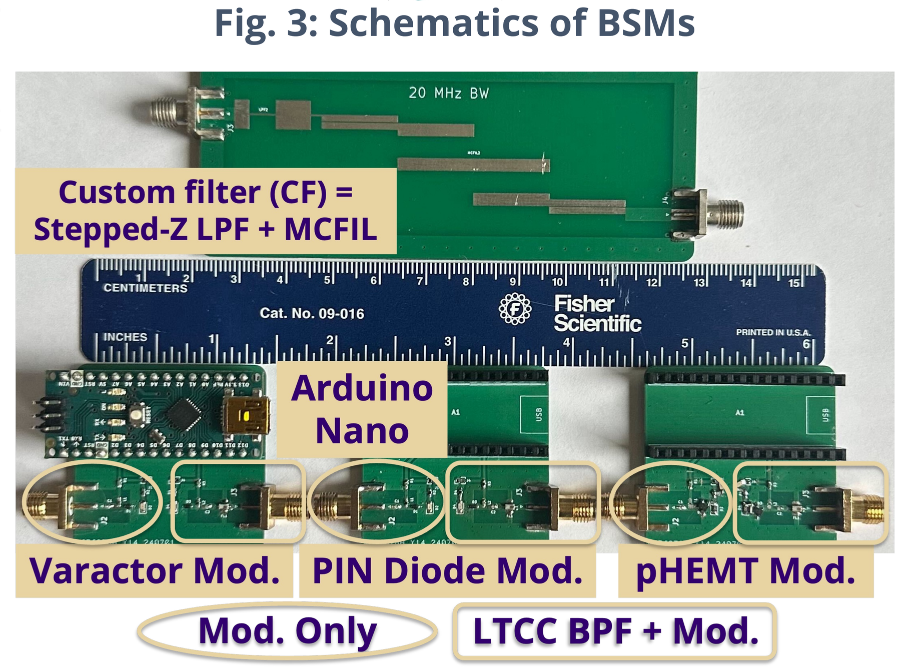


Fig. 4: Photo of PCBs

Table I: Meas. Mod. Power Consumption at 1 Mbps

Modulator Device	Avg. Power Consumption	Energy Efficiency
pHEMT	1.90 μW	1.90 pJ/bit
Varactor	46.25 μW	46.25 pJ/bit
PIN Diode	22.30 mW	22.30 nJ/bit

Measured vs Simulated Results

- A calibrated vector network analyzer was used to measure the two reflection coefficients of each modulator from 0.5–8.5 GHz → $|\Delta\Gamma_{50\Omega}|$ and $|\Delta\Gamma_A|$ determined from measurements as discussed previously
- Simulations were conducted in AWR Microwave Office
- Good qualitative agreement between meas. and sim., especially at lower frequencies. At higher frequencies, FR-4 substrate loss becomes a limiting factor

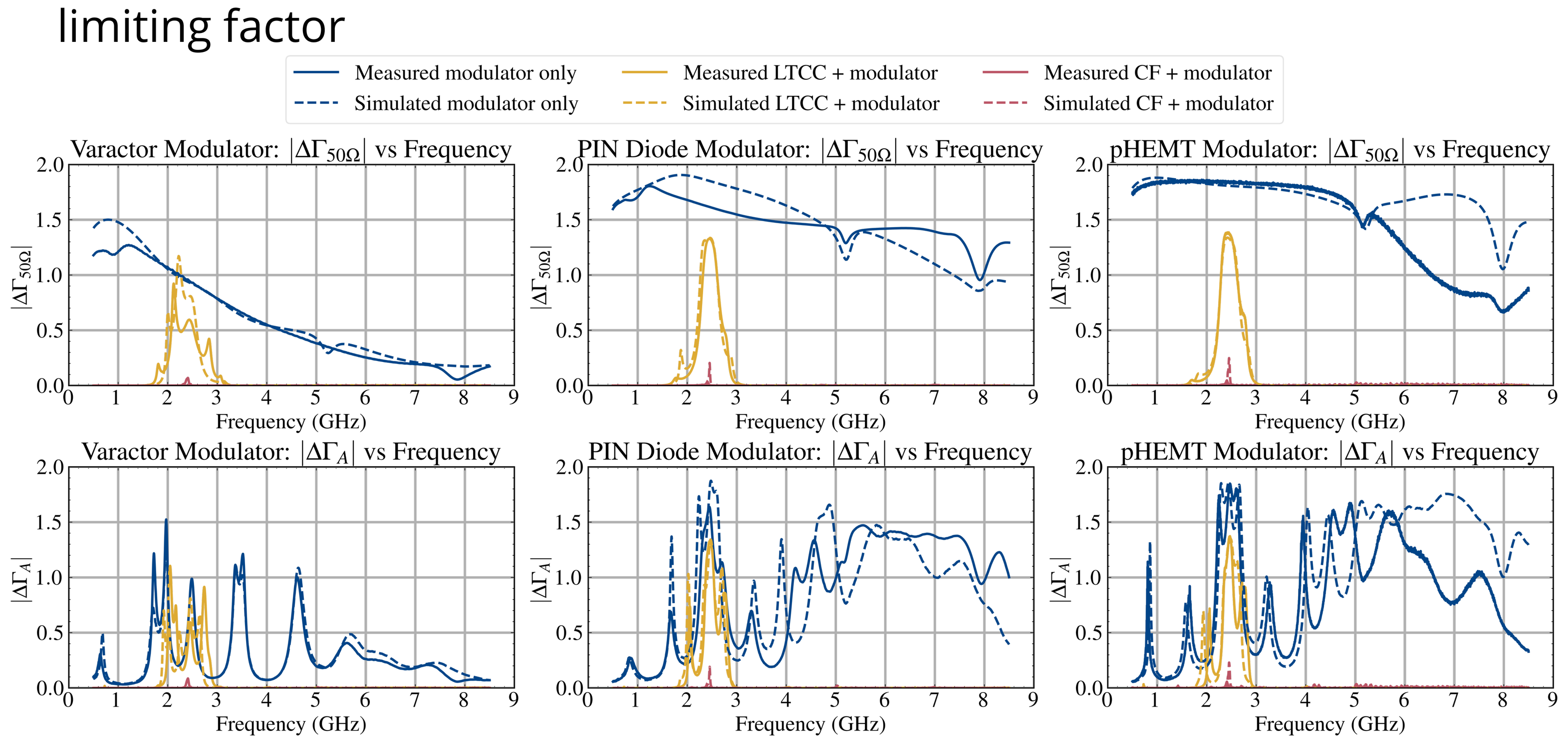


Fig. 5: Measured vs simulated $|\Delta\Gamma_{50\Omega}|$ and $|\Delta\Gamma_A|$ for modulator variants

Table II: Summary of Measured Key Metrics

	Modulator Only			LTCC BPF + Modulator			CF + Modulator		
Metric	Var.	PIN	pHEMT	Var.	PIN	pHEMT	Var.	PIN	pHEMT
Peak $|\Delta\Gamma_{50\Omega}|$, 2400-2483 MHz	0.960	1.622	1.849	0.596	1.328	1.385	0.069	0.036	0.047
$|\Delta\Gamma_{50\Omega}|$ 3dB mod. BW (MHz)	3416	7730	5856	510	308	328	50	30	28
Peak $|\Delta\Gamma_{50\Omega}|$, 4900-7200 MHz	0.396	1.437	1.655	0.004	0.003	0.004	0.003	0.007	0.025
Peak $|\Delta\Gamma_A|$, 2400-2483 MHz	0.986	1.638	1.849	0.594	1.328	1.373	0.086	0.036	0.057
$|\Delta\Gamma_A|$ 3dB mod. BW (MHz)	110	269	322	87	176	183	36	27	27
Peak $|\Delta\Gamma_A|$, 4900-7200 MHz	0.407	1.471	1.672	0.005	0.004	0.006	0.004	0.007	0.033

- **Modulator only:** high $|\Delta\Gamma|$ within 2.4 GHz ISM band, but also within antenna's higher passbands from 4900-7200 MHz
- **LTCC BPF + Modulator:** added filter eliminates $|\Delta\Gamma|$ in antenna's higher passbands, and reduces the 3dB modulation BW ($\Delta\Gamma_{3dB}$)
- **CF + Modulator:** narrower $\Delta\Gamma_{3dB}$, but severely reduced in-band $|\Delta\Gamma|$

Overall, varactor has lowest $|\Delta\Gamma|$; PIN and pHEMT exhibit similar $|\Delta\Gamma|$ levels, with drawback of higher power consumption or cost, respectively.

Next Steps

- Narrow modulation bandwidth further using reduced-size purpose-built filters, e.g. surface acoustic wave (SAW) or bulk acoustic wave (BAW) filters
- Validate approach using higher order modulation schemes and/or in other communications bands

Acknowledgments and References

[1]Unhelkar et al., *IJIM Data Insights*, 2022. [2]Toro et al., *IEEE Trans. Green Commun. Netw.*, 2022. [3]Rosenthal et al., *IEEE Trans. Microw. Theory Techn.*, 2019. [4]Thomas et al., *ACM SIGCOMM,* 2012. [5]Alhassoun, *IEEE Access*, 2023.

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