Design and Optimization of Passive Nonlinear RF Tags for the Tracking of Asian Hornets

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Résumé *— The proliferation of the Asian hornet represents a major threat to honeybee colonies across Europe. Among the available nest localization methods, passive harmonic radars offer a good compromise between cost and efficiency, but their range remains limited by the low conversion efficiency of Schottky diode tags.*

This paper presents and compares three passive nonlinear tag topologies : a simple tag, an inductive loop tag, and, for the first time, a tag based on coupled inductors. The impedances presented to the diode are optimized at $2.9\ GHz$ *and* $5.8\ GHz$ *through simulations combining ADS and CST.*

Measurements conducted in an anechoic chamber confirm an improvement of nearly $+13\ dB$ *in the radiated power with the coupled-inductor topology compared with the simple tag. These results pave the way for more efficient and lightweight passive tags, better suited for insect tracking and Asian hornet nest detection.*

1. Introduction

Following the proliferation of Asian hornets (*Vespa velutina*) that attack beehives and drastically reduce bee populations in Europe, an increasing number of initiatives are being undertaken to locate and eradicate their nests [1].

Several nest-localization techniques already exist, such as triangulation [2], optical detection (thermal imaging [3], retro-reflective imaging [4]), or tracking a hornet via active [5] or passive radio telemetry based on a harmonic radar [6].

In this work, we focus on hornet-tracking methods using radio telemetry, which are less sensitive to occluding obstacles than optical systems and, moreover, passive—due to their very low cost (5–10 € per tag) compared with active systems (200–300 € per tag).

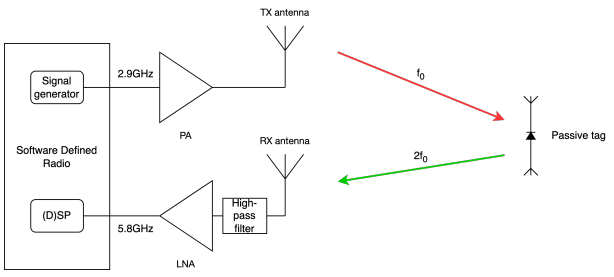

FIGURE 1. *Schematic diagram – Harmonic radar*

As illustrated in Fig. 1, the harmonic radar operates by transmitting a wave at a fundamental frequency f_0 toward a nonlinear tag, which generates harmonics of the incident signal, typically at $2f_0$ or $3f_0$. The radar receiver is tuned to these harmonics, thereby isolating the tag's response from environmental reflections at f_0.

Nonlinear tags discussed in the literature are mainly realized using a Schottky diode connected to a metallic wire acting as an antenna. Although functional, such systems are limited by the diode's low conversion efficiency, which reduces the maximum detection range. Harmonic generation within the diode remains constrained by the moderate nonlinearity of its I–V characteristic, junction capacitance effects, and mismatch losses within the tag.

To improve the performance of passive nonlinear tags, an inductance loop can be added in parallel with the diode ([7]). Another method consists in adding a complex matching circuit to enhance power transfer between the antenna and the diode [8]. However, the design methodologies of these approaches are seldom detailed in the literature ([7], [8]), and/or result in geometries that are poorly compatible with weight or size constraints for the intended application ([8]).

In this paper, we explore a new passive nonlinear tag topology for tracking Asian hornets, demonstrating enhanced performance validated by experimental measurements.

2. Methodology

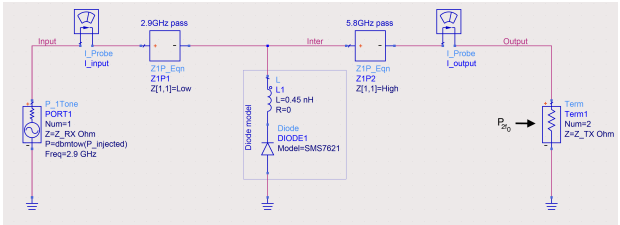

FIGURE 2. *Simulation schematic – diode impedance characterization*

As in [9], we select $f_0 = 2.9\ GHz$ and $2f_0 = 5.8\ GHz$, since this frequency pair lies within authorized (maritime) radar bands and provides an optimal trade-off between antenna size, range, and energy efficiency for short-range insect tracking [9].

The studied tag is based on the SMS7621-040LF diode [10] (where "L1" in Fig. 2 represents the parasitic inductance of the package). Its impedances at f_0 and $2f_0$ are de-

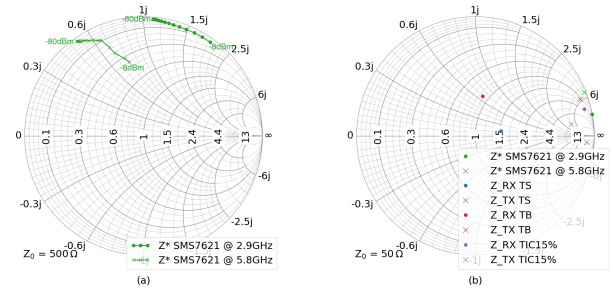

FIGURE 3. *Smith charts – conjugate diode impedances (a) and tag impedances (b)*

termined using ADS, based on the schematic in Fig. 2, by optimizing power transfer between "Z_RX" (impedance presented to the diode at f_0) and the diode at f_0, and between the diode and "Z_TX" (impedance presented to the diode at $2f_0$) at $2f_0$. P_{2f_0} represents the power absorbed by "Z_TX".

Figure 3(a) shows the evolution of the diode's (complex conjugate) impedances at $2.9\ GHz$ and $5.8\ GHz$ as a function of available power, for a reference impedance of $500\ \Omega$. It can be observed that the impedances stabilize between $-50\ dBm$ and $-80\ dBm$.

To optimize tag performance, the target impedances are taken as the diode's conjugate impedances at $-50\ dBm$, namely :

— $Z^*_{-50dBm_{2.9GHz}} = (9.75 + j544.55)\Omega$
— $Z^*_{-50dBm_{5.8GHz}} = (9.5 + j260)\Omega$

These are indicated in green in Fig. 3b.

Three tag topologies are investigated : the simple tag (ST), the loop tag (LT), and the coupled-inductor tag (CIT).

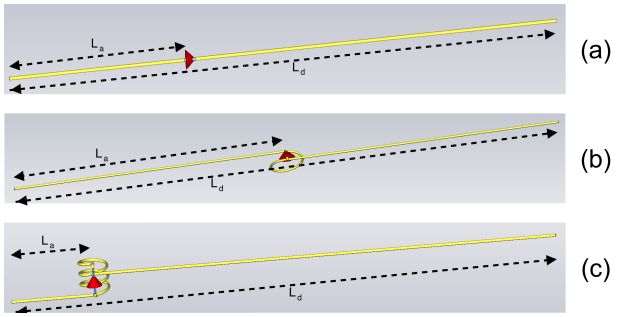

FIGURE 4. *3D models of the tags*

2.a. Simple Tag

The simple tag consists of a Schottky diode connected to both arms of a dipole (Fig. 4a) of length $L_d = \lambda/2 = 49.2\ mm$ at f_0. With its length fixed, the dipole feed point can be moved to vary "Z_TX" and "Z_RX" and maximize P_{2f_0}.

The feed position is swept from 25% to 50% of the dipole length relative to the antenna edge. The corresponding "Z_RX" and "Z_TX" impedances (blue in Fig. 3b) are computed using CST electromagnetic simulations and re-inserted into the circuit of Fig. 2 to compute P_{2f_0}.

Figure 6 shows that P_{2f_0} (and hence the radiated power) for the ST averages around $-125\ dBm$, with a slight improvement when the feed point lies between 25% and 40% of L_d.

2.b. Loop Tag

In the loop tag (LT), an inductive loop is added in parallel with the diode and dipole (Fig. 4b). The dipole feed point is again varied from 25% to 50% of its length. A maximum performance improvement is observed (red trace in Fig. 6) when the feed port is located at 45–50% and when an inductance of $L = 5.4\ nH$ is added, corresponding to a loop diameter of $3.14\ mm$ according to :

$$L = \frac{\mu_0 \mu D}{2}\left(\ln\left(\frac{8D}{d}\right) - 2\right)[H]$$

where D is the loop diameter and d is the wire diameter. This represents an approximate 10 dB increase in radiated power compared with the ST.

2.c. Coupled-Inductor Tag

Inspired by balun circuits used to transform an unbalanced transmission line into a balanced one, it is found that two coupled inductors with a common central node can improve the matching between the diode and the dipole.

This topology is simulated in ADS (Fig. 5), where the number and dimensions of the coupled inductors are varied to maximize P_{2f_0}. Again, the corresponding "Z_RX" and "Z_TX" impedances (purple in Fig. 3b) are computed in CST (Fig. 4c) and re-inserted into the circuit of Fig. 2 to compute P_{2f_0}. Figure 3b clearly shows that a better conjugate match is achieved simultaneously at f_0 and $2f_0$ with this new topology.

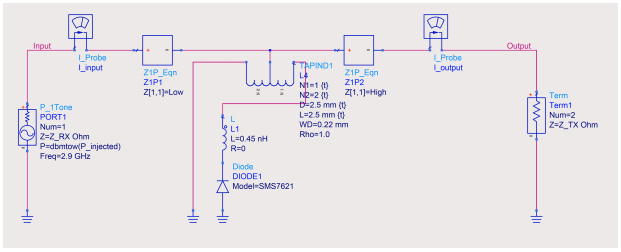

FIGURE 5. *Simulation schematic – coupled-inductor topology*

By varying the diode position from 10% to 50% of L_d, Fig. 6 shows a significant performance improvement, with a P_{2f_0} value 24 dB higher than the ST case and 15 dB higher than the LT case when the diode is placed at 15% of L_d. However, the conjugate matching is not perfect, leading to a degradation of approximately 30 dB compared with the ideal case.

3. Experimental Results

For experimental measurements, two antennas are placed equidistant from the tags in an anechoic chamber (Fig. 7). The TX antenna is connected to a signal generator and the RX antenna to a spectrum analyzer. The three tag topologies are fabricated and tested experimentally by comparing the received powers on the spectrum analyzer. The measured results (Fig. 8) are consistent with simulations and show an improvement of the LT over the ST

FIGURE 6. *Simulated P_{2f_0} value as a function of the dipole feed position.*

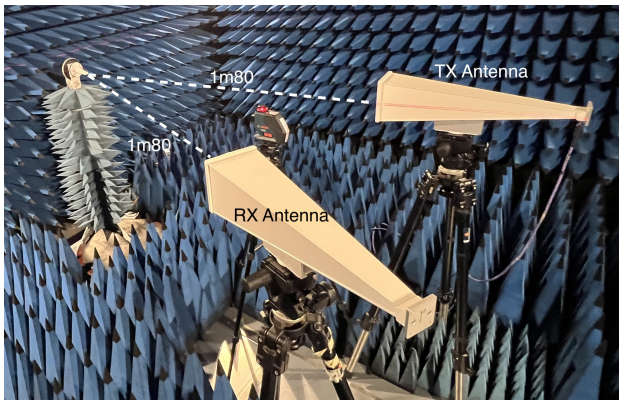

FIGURE 7. *Measurement setup in an anechoic chamber*

(about 5 dB for $L_a = 50\%L_d$). They also reveal a clear 8.5 dB enhancement of the CIT (for $L_a = 35\%L_d$) compared with the LT, corresponding to an approximate 63% increase in detection range. Further tests will be performed shortly for smaller L_a values.

4. Conclusion

This paper presents a design methodology for passive nonlinear tags based on a Schottky diode and dipole antenna for Asian hornet tracking. It also discusses optimization strategies by varying the diode position and matching components within the dipole. Finally, a novel conjugate-matching topology based on coupled inductors is proposed, offering a simple implementation and a significant ($\sim 8.5\ dB$) improvement in reradiated power compared with the conventional loop-tag topology. This improvement is experimentally validated. These results open the way for more efficient and lightweight passive tags, better suited to insect tracking and hornet nest detection.

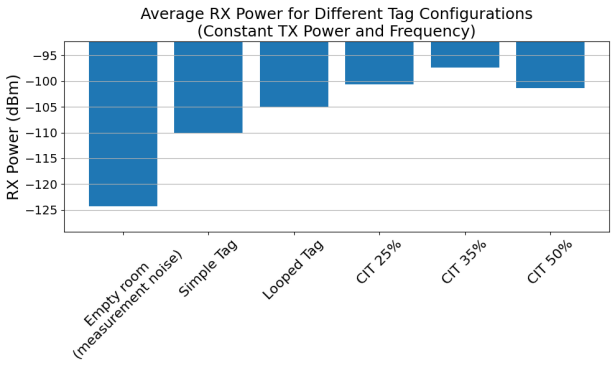

FIGURE 8. *Measured results – ST at 50%, LT at 50%*

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