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Nonlinear Measurements of Electrochromic WO₃/LiNbO₃/NiO at Microwave Frequencies

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Abstract— In this paper and for the first time, nonlinear behaviour of an electronically tuneable electrochromic (EC) thin film material is investigated experimentally at microwave frequencies. The measurement setup based on the single tone method uses identical topologies for test cells based on SiO₂ or Silicone Dioxide (SD) and EC dielectric materials for a mutual comparison study of the nonlinear behaviour of the tuneable EC dielectric. The measured third-order intercept point of EC test cells is around 80 dBm, which is larger than typical values for other tuneable technologies such as ferroelectrics and liquid crystals (LCs).

I. INTRODUCTION

Tuneable dielectric materials have potential applications in various integrated reconfigurable microwave devices, such as antennas, phase shifters and filters, to name but a few [1]. The use of this innovative control strategy requires precise characterization of the dielectric properties, and in this regard, numerous studies have been conducted to study dielectric properties of potential candidates such as ferroelectrics, [2], and liquid crystals (LC), [3].

In 2016, the authors reported [4] on high frequency tunability of inorganic Electro-Chromic (EC) materials. Further studies demonstrated that the extent of dielectric tunability can be increased tremendously, up to 60% [5-6]. However, there have been no reported studies on their nonlinear performance. This paper, for the first time ever investigates nonlinear behavior of inorganic EC materials at microwave frequencies.

II. TEST CELLS AND MEASUREMENT SETUP

Fig. 1 (a) illustrates the arrangement of a conventional EC structure that consists of five layers deposited on a substrate, usually glass. The center electrolyte, here LiNbO₃, acts as a tank of available ions and has a strong influence on the device performance. The two EC films, Tungsten trioxide (WO₃) and Nickel oxide (NiO), color and bleach by the movement of ions and electrons when a dc bias voltage is applied. Finally, two conducting electrodes sandwich the three-layer structure.

The topology of test cells used for nonlinear measurements is shown in Fig. 1 (b). Each cell consists of two CPW-to-microstrip transitions located at the two ends of a microstrip line section with length L . For EC cells, the microstrip line section

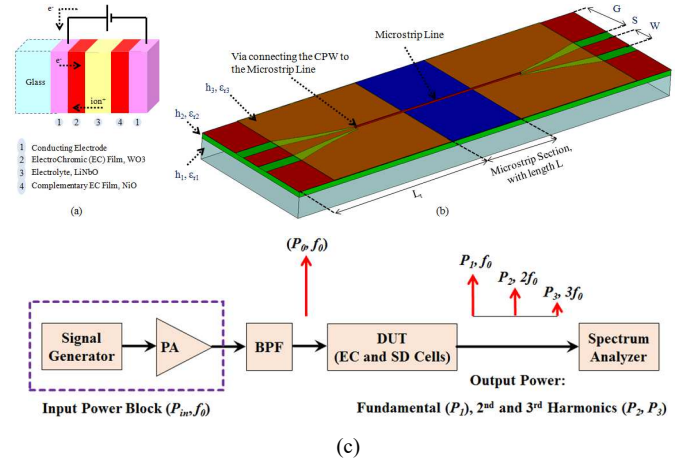


Fig. 1. Multi-layer EC material topology, (b) Cell topology, (c) Nonlinear measurement setup

hosts the multi-layer EC composite material as the dielectric material while for SD is used.

Various lengths of the microstrip line sections ($L = 0, 1, 2$ and 5 mm) patterned on both SD and EC material are measured and discussed here. The reason for such an extensive measurement synthesis is to 1) investigate the effect of the cell length on the nonlinear response and 2) provide an in-depth intercomparison study on the nonlinear response of the EC material with respect to SD. It is obvious that such a comparative study is most beneficial considering the fact that EC and SD cells are identical in geometry, fabrication and measurements.

A single-tone method is used to measure nonlinear distortions. For this, a continuous wave signal at frequency f_0 is applied to the Device-Under-Test (DUT) and the second and third harmonics are measured at the output port at frequencies $2f_0$ and $3f_0$, respectively. Fig. 1 (c) shows the measurement setup that consists of a signal generator, a power amplifier (PA), a bandpass filter (BPF), the DUT and a spectrum analyzer. The signal generator (R&S SMU200A) in conjunction with the PA provide a gain of about 33 dB at the center frequency of $f_0 = 1.9$ GHz. The 5-pole cavity BPF has an insertion loss of

about 1 dB at f_0 , and is designed to suppress harmonics generated by PA up to -80 dBc.

Finally, the measured reflection coefficient at $f_0 = 1.9$ GHz is less than -7.5 dB for both EC and SD cells, which is low enough to ensure that power transmission is sufficiently high. The input power denoted by P_{in} fed to the BPF in Fig. 1 (c) varies from 20 dBm to 30 dBm in steps of 2 dB.

III. RESULTS

Fig. 2 shows the measured second (P_2) and third harmonic (P_3) power levels generated at the output port of the 1 mm, 2 mm and 5 mm long SD and EC cells. Here, the measured harmonics are shown versus the power of the fundamental tone (P_1) measured at the output port. Additionally, the curves corresponding to the residual level of the test setup (without DUT) and the results for the cell employing two transitions in a Back-To-Back (BTB) configuration ($L = 0$ mm) are shown in Fig. 2.

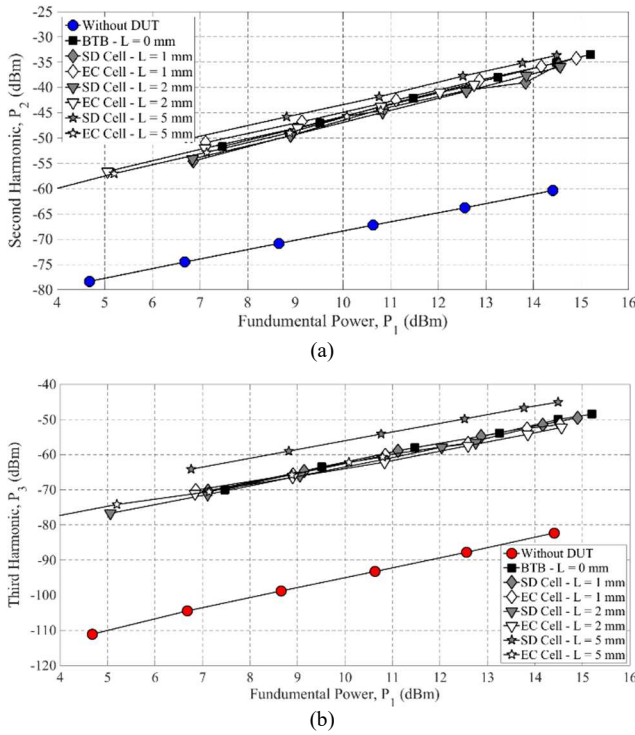


Fig. 2. Measured (a) second and (b) third harmonics vs. fundamental tone for SD and EC cells. Residual level of test setup (without DUT) is also shown.

It is evident from both graphs in Fig. 2 that all DUTs produce a level of second and third harmonics that is distinctively higher than the residual level of the test setup. This indicates the existence of a nonlinear source within the DUT itself, attributable to either the dielectric materials (EC or SD) or to a microstrip line. The identical trend observed for all cells (SD and EC) suggests that the main source of nonlinearity must be related to a structure common to all DUTs; namely, the CPW-to-microstrip transitions. To confirm this, the results for the BTB cell ($L = 0$ mm) of Fig. 2 indicate that this is indeed the case, as the level of nonlinear products does not significantly vary as a function of the test cell length. This infers that inorganic EC structures examined here are inherently linear. This point is further reinforced by the results in Fig. 3, which shows the third-

order intercept diagram for both EC and SD cells. The measured Third-Order Intercept (TOI) points for both the EC and SD cells are almost identical and are equal to 74 dBm which is good enough for many high-power RF applications. A higher TOI value is expected for EC-based cells using an alternative realization of the CPW-to-microstrip transition. In any case, the measured TOI point of EC cells is considerably higher than the TOI values reported for all other tuneable materials, e.g., ferroelectrics (60 dBm and less, [2]), LCs (65 dBm and less, [3]) and graphene (28 dBm, [7]).

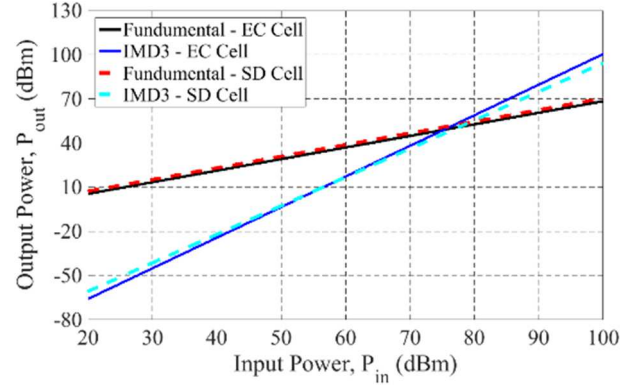


Fig. 3. Third order intercept diagram of EC and SD cells with $L = 2$ mm. The IMD3 curves are obtained from the relation $IMD3 = P_3 + 9.54$ dB.

IV. CONCLUSION

Nonlinear performance of inorganic EC materials was investigated for the first time. It was shown that the level of nonlinearities of EC material is very low and that in the tested cells the nonlinear response is caused mainly by CPW-to-microstrip transitions. The measured TOI point is much higher than competing tuneable technologies, such as graphene or LC.

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