Tunable polarization response of a planar asymmetric-spiral infrared antenna

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Received September 9, 1998

We present measurements at 10.6 μm that demonstrate electronic tuning of the polarization response of asymmetric-spiral infrared antennas connected to Ni–NiO–Ni diodes. Continuous variation of the bias voltage applied to the diode results in a rotation of the principal axis of the polarization ellipse of the spiral antenna. A 90° tuning range is measured for a bias voltage that varies from −160 to +160 mV. This effect is caused by a small asymmetry of the deposited diode contact or by a variation of the detector capacitance with the applied bias voltage. © 1998 Optical Society of America

OCIS codes: 040.0040, 040.1880, 040.3060, 230.5440.

Advances in microfabrication techniques permit the manufacture of planar lithographic antennas with complicated geometries at submicrometer dimensions. These tiny antennas are used for coupling infrared radiation with wavelengths near 10 μm to ultrafast detectors with dimensions of the order of 0.1 μm. A review of the development of antenna-coupled thin-film Ni–NiO–Ni diodes as detectors and mixers for 10.6-μm radiation was published in Ref. 1. The dominant detection mechanism in these devices is rectification by the diode nonlinearity of terahertz current waves induced in the antenna. In the present Letter we describe the tunability of the polarization response of asymmetric spiral antennas connected to this type of diode. The polarization response of these planar spiral antennas was investigated in Ref. 2, in which the measured wavelength dependence of the detected signal was explained by a model that considered the vector sum of the two fundamental modes propagating on the arms of the spiral: the balanced and unbalanced modes with amplitudes B and U, respectively. The imbalance is caused by the reactive impedance of the diode. The ratio U/B, influenced by the capacitance of the diode, determines the orientation of the principal axis of the polarization ellipse of the detector response. From the conclusions of this model, a change in the polarization response of the detector is expected when the mode ratio U/B is varied. This variation is achieved by a change in the bias voltage applied to our Ni–NiO–Ni detector.

The antenna-coupled detectors used for the present experiments were described in Ref. 2. Figure 1 is a photograph of an antenna-coupled Ni–NiO–Ni diode. The two arms of the spiral antenna are manufactured as two separate metal depositions. The structures are defined with direct-writing e-beam lithography. The asymmetry at the origin of the spiral is used to relax the alignment tolerance for the relative positions of the two arms. A sputtered 3.5-nm NiO layer between the two Ni layers produces the tunnel diode.

The experiments were performed in the same arrangement as described in Ref. 2. However, in the present experiment the CO_2 laser is tuned to one particular transition [10P(20)] at a wavelength of 10.591 μm and the bias voltage is varied from −160 to +160 mV. For each value of the bias voltage, the diode response as a function of polarization angle is measured over a 240° range in increments of 6°. An example measured at a bias voltage of 4.8 mV is displayed in Fig. 2.

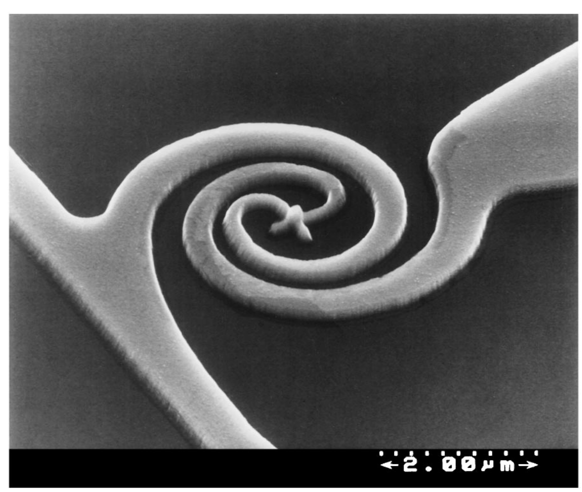

Fig. 1. Electron micrograph of a Ni–NiO–Ni diode with an integrated asymmetric spiral antenna.

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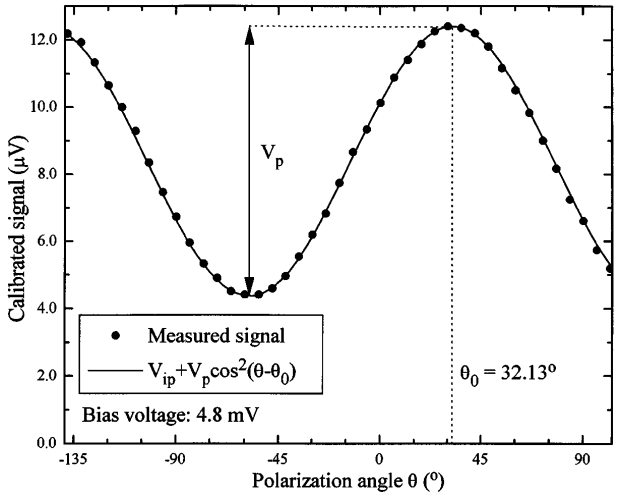

Fig. 2. Polarization dependence of the Ni–NiO–Ni diode response at a bias voltage of 4.8 mV. Fitting of the curve permits determination of θ_0. In the fitting function, V_p represents the polarization-dependent part of the signal (antenna signal) and $V_{\rm ip}$ represents the polarization-independent part of the signal (partly thermal).

Fitting of the data with a biased sinusoid (Fig. 2) permits accurate determination of the polarization orientation θ_0 for maximal response. The angle θ_0 characterizes the orientation of the principal axis of the polarization ellipse of the spiral antenna. These measurements and fitting procedures were performed for 24 values of the bias voltage from -160 to $+160$ mV. The results of our measurements are plotted in Fig. 3 as a function of the bias voltage. In this figure the filled circles represent the angles θ_0 determined experimentally as a function of the bias voltage applied to the diode. The results are plotted for the range of maximum change in θ_0, from -40 to $+40$ mV. The measured angles θ_0 are asymptotically stable for higher bias voltages. Also represented in Fig. 3 is the measured amplitude V_p (defined in Fig. 2) of the oscillation of the measured signal as a function of the bias voltage.

The transition from negative to positive bias permits a 90° tuning of the orientation of the principal axis of the polarization ellipse of the spiral antenna. This tuning can be plausibly explained on the basis of the model presented in Ref. 2. The polarization response of our antenna-coupled devices is determined by the ratio of the amplitude of the two fundamental modes that propagate on the antenna: Beside the balanced mode, a significant unbalanced mode exists on the antenna arms and is likely to be caused by the reactive impedance of the diode. We observe the polarization-tuning effect for bias voltages near zero. In this region the small asymmetry of the contact may be responsible for the continuous sign change. The two modes involved in the radiation-coupling process possess slightly different bias voltage values for their sign change. The plausibility of this explanation is shown with the following simulation: The dashed curve in Fig. 3 is calculated as the angle for maximum polarization response for the sum of two modes with different polarization responses. These two modes correspond to the balanced and the unbalanced modes of our model.[2] The amplitudes of the two modes of our simulation possess a linear dependence on the bias voltage but do not have the sign change at exactly zero bias voltage. These mode amplitudes as functions of $V_{\rm bias}$ are represented in Fig. 4 (top) and are simulated as follows:

$$B(V_{\rm bias}) = A_B \times (V_{\rm bias} - V_{B-0})\,, \tag{1a}$$

$$U(V_{\rm bias}) = A_U \times (V_{\rm bias} - V_{U-0})\,. \tag{1b}$$

Each of the modes consequently has a zero response at a finite bias voltage ($V_{B-0} = -3$ mV and $V_{U-0} = -8$ mV). The ratio U/B of the two mode amplitudes is represented in Fig. 4 (bottom). For high bias voltages, this ratio has an asymptotic limit that corresponds to the value U/B determined in Ref. 2:

$$\frac{U}{B}(V_{\rm bias}) = \frac{A_U \times (V_{\rm bias} - V_{U-0})}{A_B \times (V_{\rm bias} - V_{B-0})}\,,$$

$$\frac{U}{B}(\pm\infty) \approx \frac{A_U}{A_B} = 0.75\,. \tag{2}$$

The ratio U/B is consequently stable near 0.75 for high-bias voltages but varies quickly near zero bias. The resultant simulated curve $\theta_0(V_{\rm bias})$ shown in Fig. 3 accurately describes the measured data. The solid curve of Fig. 3 is computed with the same simulation and describes the behavior of the signal amplitude $V_p(V_{\rm bias})$. The transition occurs not at $V_{\rm bias} = 0$ mV but at $V_{\rm bias} = -4.6$ mV. The asymmetry can be explained by a small intrinsic asymmetry of the diode: The Ni layer in direct contact with the substrate is overlapped by the second Ni layer.

The variation of mode ratio U/B with bias voltage $V_{\rm bias}$ may be caused by a variation of the

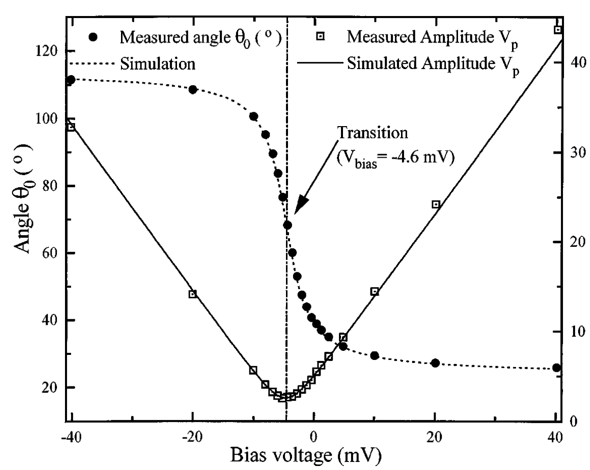

Fig. 3. Orientation θ_0 of the principal axis of the polarization ellipse of the spiral antenna as a function of the bias voltage. The measured amplitude V_p of the polarization-dependent part of the diode signal is also plotted and is related to the right-hand axis.

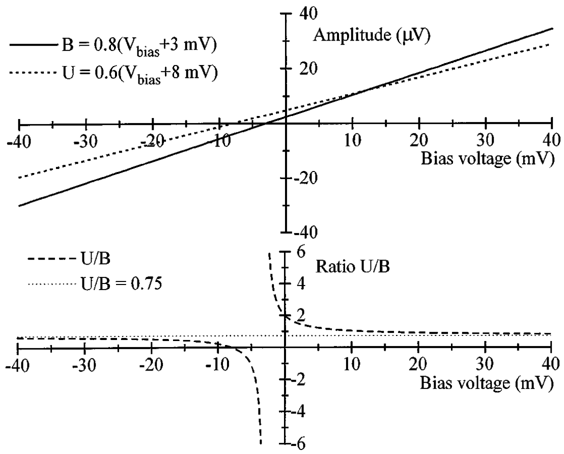

Fig. 4. Top, bias voltage dependence of mode amplitudes U and B used in the simulation of Fig. 3. Bottom, corresponding bias voltage dependence of mode ratio U/B.

capacitance of the junction with V_{bias}. A dc capacitance in a 0.13-fF range is estimated for our Ni–NiO–Ni detector.[1] The transition from negative to positive bias voltage induces a variation of the capacitance of the diode, in a manner similar to that of other barrier diodes.[3,4] The capacitance-against-voltage characteristic $C(V)$ of our device is expected to be nearly symmetrical, resulting from the use of Ni as the metal on both sides of the oxide barrier, with a maximum for V_{bias} near 0 mV. For positive or negative high-bias voltages ($|V_{\text{bias}}| > 50$ mV), a saturated behavior of the $C(V)$ curve would explain the asymptotic stability of $\theta_0(V_{\text{bias}})$. This behavior is consistent with the observed effect.

Our measurements demonstrate the polarization tunability of our infrared antennas. The observed effect takes place in the region of the sign transition of the detector signal, near zero bias, where the detector responsivity is the lowest (Fig. 3). Enhancing the asymmetry of the contact, for example, by using two metals with different work functions as electrodes, is expected to produce a transition that occurs away from zero bias. This asymmetry should produce a sensor with a polarization transition at a region with higher responsivity.

In conclusion, we have achieved 90° polarization tuning of Ni–NiO–Ni diodes connected to an infrared asymmetric spiral antenna by varying the bias voltage applied to the device from −160 to +160 mV. The mechanism of this electronic polarization tuning is postulated to be a bias voltage dependence of the amplitude ratio of the modes propagating on the spiral antenna. This mechanism is caused by the small asymmetry of the I-V characteristic of the diode or by the variation of the diode capacitance with bias voltage. Our measurements were achieved with diodes that were not designed for these purposes. The results point to a fast, high-responsivity electronic polarization agility that should be possible with optimized devices. Detectors of this type would be useful for real-time polarization-sensitive detection of infrared radiation, with applications in imaging polarimetry.

This study was supported by the Swiss Defense Procurement Agency, Bern; the Swiss Federal Institute of Technology (ETH), Zürich; and IBM Research Laboratory, Rüschlikon, Switzerland. G. D. Boreman acknowledges the support of the Ballistic Missile Defense Organization. When this research was performed, C. Fumeaux was a Ph.D. degree student at the ETH. C. Fumeaux's e-mail address is cfumeaux@mail.creol.ucf.edu.

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