



Khawaja, B. A. M., & Cryan, M. J. (2008). A millimetre wave phase shifter using a 40GHz hybrid mode locked laser. In 4th IEEE International Conference on Emerging Technologies 2008 (ICET 2008), Rawalpindi, Pakistan. (pp. 87 - 91). Institute of Electrical and Electronics Engineers (IEEE). 10.1109/ICET.2008.4777480

Link to published version (if available):  
[10.1109/ICET.2008.4777480](https://doi.org/10.1109/ICET.2008.4777480)

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# A Millimetre Wave Phase Shifter Using a 40GHz Hybrid Mode Locked Laser

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**Abstract**—In this paper, electrical injection locking of a mode-locked laser is used to create a millimetre wave phase shifter. The phase shift is measured directly using a vector network analyzer enabling straightforward characterization of such systems. Both magnitude and phase of the modulation response are measured and for sufficiently high RF input power a “plateau” is observed in the magnitude response which corresponds to the locking range of the system. Phase shifts of greater than  $90^\circ$  are observed and such devices could have applications in millimetre wave radio-over-fibre phased array antenna systems.

**Keywords**—component; Injection locking; Mode-locked laser; Millimetre wave; Phase shifter, Radio-over-fibre, Phased array antennas systems.

## I. INTRODUCTION

Monolithic mode-locked semiconductor lasers operating at  $1.5\mu\text{m}$  wavelength are used in a number of applications including optical clock extraction [1], optical time division multiplexing (OTDM) / packet switching [2] and radio-over-fibre (RoF) communication systems [3]. Typically mode locked lasers (MLLs) are fabricated from a standard Fabry-Perot (FP) laser which has a short saturable absorber (SA) section placed within the cavity. When the SA section is reversed biased longitudinal modes within the cavity become synchronized. This results in the pulsed emission of light with a repetition frequency determined by the cavity round trip time. For typical device lengths around  $1\text{mm}$  this results in millimetre wave (mm-wave) repetition frequencies and thus in combination with high speed photodiodes can be used as millimetre wave sources. It is well known that by inputting an RF signal into the SA section injection locking can occur where the “free running” frequency of the MLL becomes controlled by the injection signal. This is the hybrid mode-locking regime which results in very stable, low phase noise signals which are important in a number of optical communications applications.

Georges et al. [4, 5] showed that this approach can be used to directly modulate lasers well beyond their conventional bandwidths and that baseband data can be transmitted using such techniques. This makes these devices ideal low cost sources for mm-wave radio-over-fibre systems which traditionally rely on expensive external modulators in the mm-wave bands. In [4] it was shown that the phase locking that occurs enables mm-wave phase shifting to be implemented.

This occurs due the fact that under injection locked conditions the mm-wave frequency of the MLL is controlled by the external locking signal. Thus, if an attempt is made to change the MLL frequency by changing the SA bias for example, the MLL frequency cannot change and thus the only option available for the system is a change in phase. This has important applications in RoF systems, in particular in phased array antennas [4] where long fibre links can be used to send mm-wave signals to arrays of many thousands of antennas. Typically each antenna element would require its own electronic phase shifter and associated control circuitry, this MLL based technique enables this to be preformed completely remotely from the antenna, reducing the requirement at the array to a photodiode and amplifier in each element.

This paper presents a study of a mm-wave phase shifter using state-of-the-art 40GHz hybrid MLLs and shows a novel technique to characterize the phase-locking phenomenon which uses the phase locked nature of a vector network analyzer (VNA). These phase shifting techniques have applications in low cost smart antenna systems for mm-wave wireless LANs (WLANs) where antenna arrays could scan an office environment with multiple beams to deliver very high speed wireless internet. These will most likely be at 60GHz [6] and this frequency can be achieved by reducing the MLL device length or employing harmonic mode-locking schemes. Here we present the results using MLLs at the prototype frequency of 40GHz which shows their suitability for next generation 60GHz WLANs systems where 4GB/s data transmission is possible and radio-over-fibre systems employing MLLs as mm-wave sources are looking like strong candidates. This is due to the difficulties in transmitting 4GB/s baseband data over 10-100's of metres using conventional copper cables, followed by upconversion to 60GHz at an Access Point.

## II. MEASUREMENT SETUPS

The MLLs used for the measurements have been supplied by HHI, Berlin [2]. They are multi-section devices comprising SA, gain and phase sections along with a DBR for wavelength tuning. The total length of the device was  $1080\mu\text{m}$  which produces an output pulse repetition rate of around 40GHz. Two MLLs were characterised for these measurements and will be referred as MLL-A1 and MLL-A2 respectively.

To study the effect of input RF power at the S.A section of the MLLs and to measure the amount of phase shift achievable

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The Author Bilal A. Khawaja would like to acknowledge National University of Science and Technology (NUST), Pakistan for providing PhD. funding.

and its dependence on the input RF power, three different configurations have been tried. For the simplest configuration, port 1 of a VNA is used to input a mm-wave signal into the SA section to produce hybrid mode locking. Light is coupled out of the laser and into a high speed photodiode and back into port 2 of the VNA. In the other two setup configurations mm-wave amplifiers were used as shown in Figure 1 (a) and (b) below.

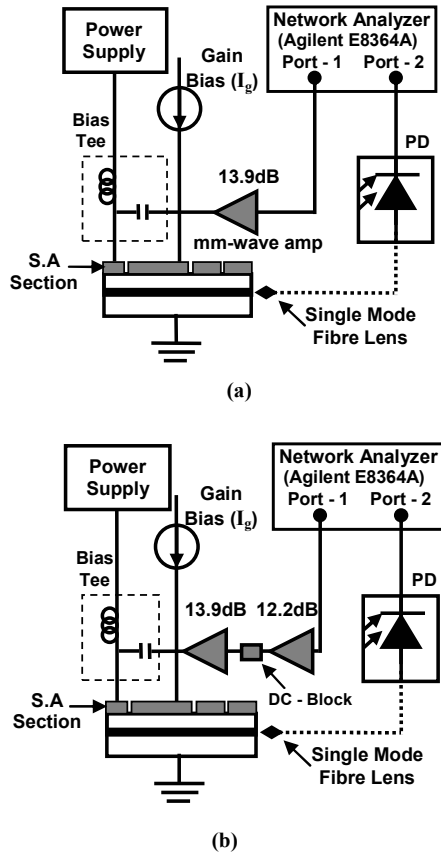


Figure 1. MLL-A2 measurement setup (a) Using one mm-wave amplifier, (b) Using two mm-wave amplifiers in series with a DC-block for higher RF input power to the S.A section

In Figure 1 (a) one mm-wave amplifier was used to measure the response of the MLL-A2 then the same measurements were repeated with two mm-wave amplifiers in series. Care must be taken with DC current leakage between the amplifiers and a DC-block was used for this purpose. The measurement of  $S_{21}$  characterizes the modulation response of the system in terms of both magnitude and phase by using setup shown figure 1. Across the locking range of the MLL a strongly enhanced modulation response is observed which is well beyond the conventional direct modulation bandwidth. The locking range is observed as a flat “plateau” in the  $S_{21}$  amplitude response where the swept frequency of the VNA is locking the free running frequency of the MLL. Parameters of the MLL can then be changed and the induced phase shift can be observed directly.

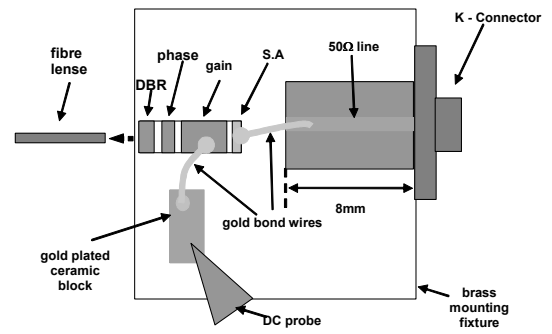


Figure 2. Schematic of mounting configuration for MLL testing

Figure 2 shows the device mounting configuration. The MLLs were mounted on brass fixtures and the gain section was connected using a bond wire to a separate gold plated ceramic block which was then probed to apply the forward bias to the gain section. A K-connector, 50Ω transmission line and gold wire bond are used to apply both RF power and reverse bias to the S.A section for hybrid mode-locking, this utilizes the built-in bias tees within the VNA. Care must be taken with the design of microstrip line, length of bond wire and transition from K-connector in order to ensure good performance at 40GHz.

### III. RESULTS

Both MLL-A1 and MLL-A2 have excellent output power characteristics giving more than 5mW and 3.5mW of optical power into a fibre lens respectively at 15°C and 50mA gain section current. Initially passive mode locking results are presented. Using MLL-A1 and MLL-A2, the gain section is forward biased with 110mA and the SA voltage,  $V_{sa} = -1.0V$ . The mm-wave spectrum is observed using a high speed U<sup>2</sup>T Photonics 50GHz photodetector and an Agilent 50GHz spectrum analyzer. The results are shown in figure 3 and a well defined mode locking spectrum is observed. One important point to note here is that although same bias are applied to both the MLLs their locking frequencies and spectra are slightly different. This shows the device-to-device variation that occurs within MLL devices.

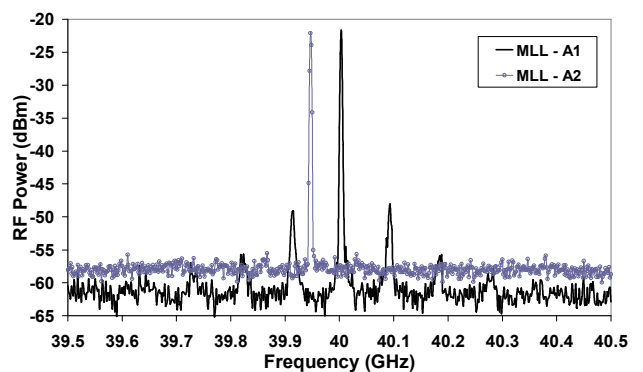


Figure 3. Measured Millimetrewave spectrum of passive mode locking at  $V_{sa} = -1.0V$  for MLL-A1 and MLL-A2

The free running frequency of the MLL can be controlled by the SA voltage and gain section bias and has a range of 446.7MHz from 39.6816-40.1283GHz for a range of SA voltages from -1.5 to -0.5V and gain section bias currents of 90mA – 150mA respectively as shown in figure 4. The free running frequency tuning range is an important parameter in these types of systems. It is well known from injection locking of electronic oscillators that this will control the amount of available phase shift [7-9]. It should be remembered however, that the hybrid mode locking regime described here will be much more complex than the Van Der Pol-like oscillators studied in [7, 8].

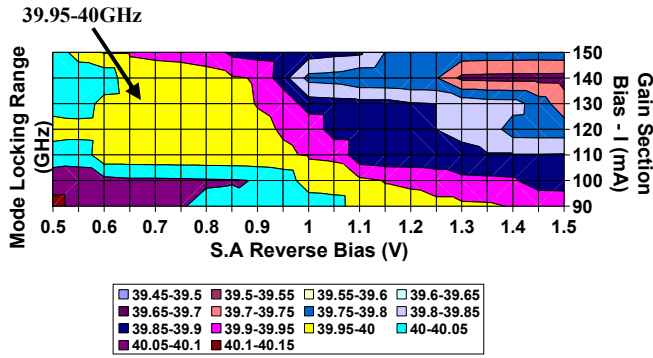


Figure 4. Shows the tuning range for passive mode locking at  $V_{sa} = -0.5V$  to  $-1.5V$  and  $I_g = 90mA$  to  $150mA$

Hybrid mode locking is then performed by RF injection locking of MLL-A2 as shown in Figure 1a and 1b. The gain section was biased at 110mA and the S.A section was biased at range of voltages from -0.5V to -1.5V. The phase and DBR sections were unbiased for these measurements. Port 1 of the VNA is connected to a Hittite (HMC-ALH369) mm-wave GaAs low noise amplifier (+13.9dB gain) and then to the S.A and the output of the MLL is fed through the single mode U<sup>2</sup>T Photonics (XPDV-2020R) 50GHz photodetector and back into port 2 of VNA for the first set of measurements then the same setup was repeated with a second +12.2dB gain mm-wave amplifier for higher RF input power into the S.A section. In electronic oscillators based systems [7-9] the amount of injected power is an important parameter with greater input power producing increased locking ranges. Figure 5 shows the amplitude of the modulation response. The low frequency modulation response can be seen to roll off around 5-10GHz, however, strong resonant enhancement is observed around 40GHz across the locking range of the MLL.

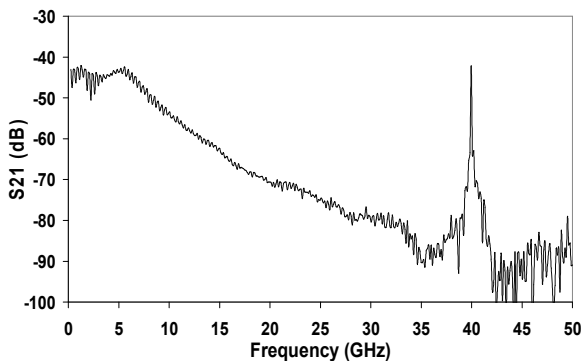


Figure 5. Modulation Response of MLL-A2 under hybrid injection locking with gain section current of 110mA and  $V_{sa} = -1.1V$

### A. Low Injection Power Results

Figure 6 below shows a zoom-in of the amplitude response of MLL-A2 when no amplifier was connected to the S.A section of the laser.

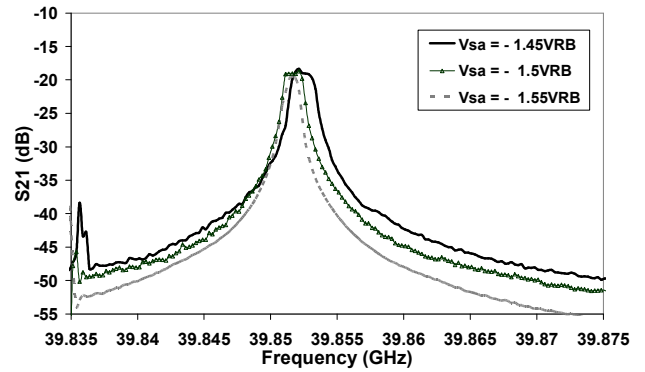


Figure 6. Zoom-in on amplitude of modulation response across the locking range for different SA reverse bias values

The maximum VNA output power is -6dBm at 40GHz which after the V-K connectors results in -8dBm input to the laser fixture. The loss from connector to SA section is estimated from separate fixture measurements to be 2dB, thus the input power to the SA will be estimated to be -10dBm in this case. The amount of power delivered to the SA will be less than this due to mismatch loss. This is difficult to quantify using the hybrid techniques used here and an in-house wafer probe station will be used in future work. This amount of input power is much less than is typically used for these MLL devices which was >10dBm in [2] and accounts for the quite narrow locking ranges observed here. The phase measuring capability of VNA can now be used to observe the phase response and this is shown in figure 7 below. The results have been normalised to the phase at  $V_{sa} = -1.45V$ .

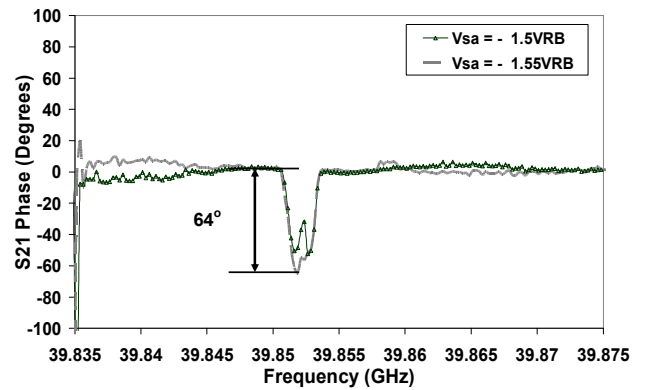


Figure 7. Shows the injection locked Phase response at S.A reverse bias of 1.5V and 1.55V, normalised to  $V_{sa} = -1.45V$

A maximum phase shift of 64° is obtained in this case when the injected RF power is as low as -10dBm. An important point to note here is the phase shift occurs only within the locking range between 39.85-39.855GHz in figure 7 and outside the phase is relatively unchanged.

### B. Single Stage Amplifier Results

The maximum VNA output power is -6dBm. To compensate this, a +13.9dB gain mm-wave amplifier was used to increase the amount of injected RF power to the S.A section. After the amplifier, bias-T and V-K connectors +2.6dBm input to the laser fixture is available which after the 2dB loss of bondwire and transmission line results in +0.6dBm input power to the SA section. This is still quite low input power but this power level is sufficient to observe locking ranges and larger phase shift performance. Figure 8 shows a zoom-in on the “plateau” region described above. It can be seen that the locking range can be tuned by changing the S.A bias and the widest locking range occurs at  $V_{sa}=-1.45V$  and is 3.88MHz.

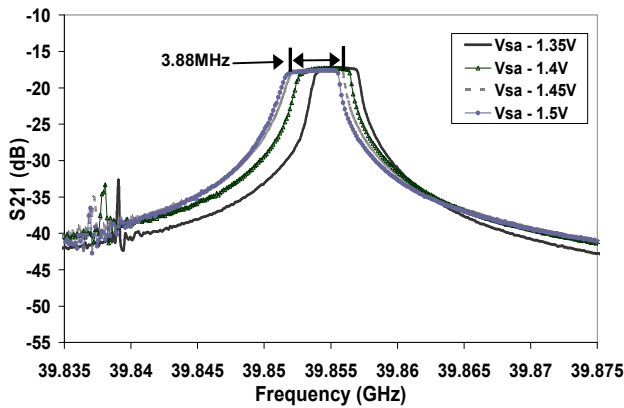


Figure 8. Zoom-in on amplitude of modulation response showing plateau across locking range for different SA reverse bias values.

Figure 9 shows the phase shift results. It can be seen that a phase shift of over 90° can be obtained over a narrow range of frequencies and across the range of  $V_{sa}$  values the amplitude response remains relatively flat resulting in good phase shifter performance. Also the phase shift occurs only within the locking range between 39.85-39.86GHz as expected.

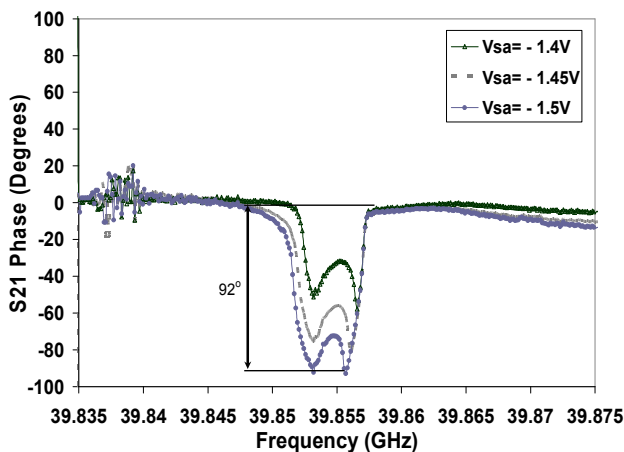


Figure 9. Shows the injection locked Phase response at S.A reverse bias of 1.4V to 1.5V, normalised to  $V_{sa}=-1.35$

### C. Two Stage Amplifier Results

Two amplifiers were then connected in series as shown in figure 1(b). There were two issues in this setup. The first one is the DC current leakage from one amplifier to the other because both the amplifiers are mounted on K-conductor fixtures and also biased-up separately. To overcome this problem a DC block was used. The two amplifier’s gain with the DC block was measured separately using VNA which was 15dB. The other issue was saturation of the second amplifier which was solved by lowering the VNA injected power level to -9.5dBm. After the first amplifier and the dc block the input power to the second amplifier is -0.4dBm which after the +12.2dB gain, bias-T and V-K connectors is +7dBm input to the laser fixture and eventually approximately +5dBm to the S.A section of the MLL.

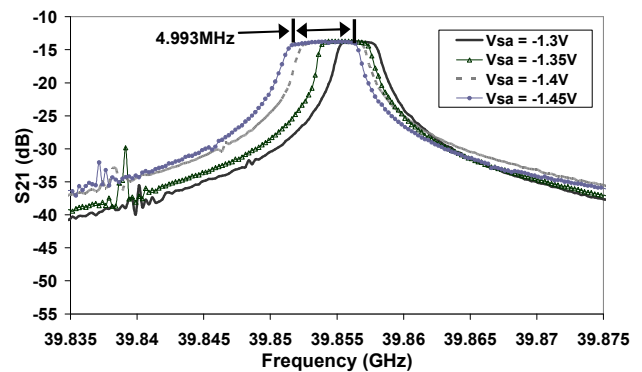


Figure 10. Zoom-in on amplitude of modulation response showing plateau across locking range for different SA reverse bias values.

Figure 10 shows the amplitude response. Two important points to note are the increase in the level of the plateau and the wider locking range which both result from the higher injected RF power to the S.A section. Figure 11 then shows the measured phase shift as a function of S.A voltage.

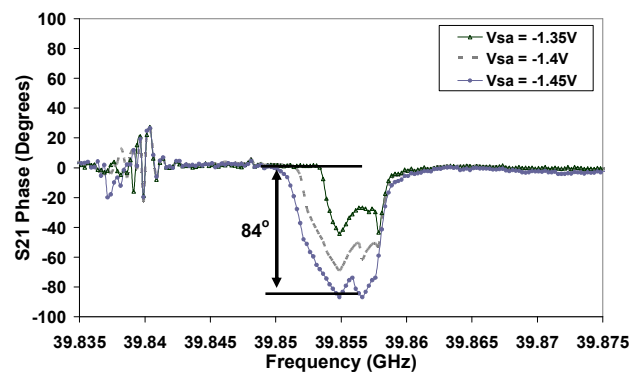


Figure 11. Shows the injection locked Phase response at S.A reverse bias of 1.35V to 1.45V, normalised to  $V_{sa}=-1.3$

In this case a phase shift of over 84° can be obtained over a narrow range of frequencies. Again for the specific range of  $V_{sa}$  values the amplitude response is remaining relatively flat resulting in good phase shifter performance.

#### IV. CONCLUSION

This paper has shown how a mode locked laser can be used under RF injection locking to perform millimetre wave phase shift and how a VNA can be used to directly measure the induced phase shift in a hybrid mode locked laser system, enabling straightforward characterisation of such systems. Such devices could have application in low cost wireless LAN smart antenna systems especially at 60GHz where radio-over-fibre is looking like a promising technology. This paper has explored tuning of the SA voltage, these devices can also be tuned with the gain, phase and DBR sections which should result in a number of novel configurations.

#### ACKNOWLEDGMENT

The authors would like to acknowledge funding from the Department of Electrical and Electronic Engineering, University of Bristol, UK.

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