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Design and simulation of optoelectronic oscillator with micro ring resonator and radio frequency amplifier modelling at 110 GHz

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There is an increasing need for high performance oscillators as the faster transmission networks demand for high frequency signals. Opto-electronic oscillators (OEO) enable us to make better oscillators in terms of size, weight and power. In this paper, photonic integration is proposed for realizing the OEO with micro ring resonator (MRR) and radio-frequency (RF) amplifiers of monolithic microwave integrated circuit (MMIC), which can be used for generating 110 GHz sine wave. The OEO architecture is proposed and block diagram developed considering Silicon based MRR and three-stage RF amplifier based on GaN high-electron-mobility transistor (HEMT). A simulation model is developed according to the Klein model of MRR and is validated against the calculated performance parameters. MRR dimensions are calculated as with silicon on insulator (SOI) technology and a radius 5.27 μm for the device is derived. Free spectral range (FSR) of 48.52 nm and filter rejection ratio of 16.79 dB are obtained for this device. The proposed RF amplifier is modelled with GaN parameters derived from high frequency pinch-off model and with power amplifier considerations. The gain for this amplifier is obtained as 10.6 dB. The OEO design is developed in this project in such a way that the system can be manufactured with the existing methods.

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The fascinating developments happening in the fields of high data traffic communications, such as 5G is a driving factor towards the development of electronic oscillators with high purity at millimeter wave frequency ranges. High-end technology applications are required to be employed in payload satellites and military radars because they need ultra-pure signal as an important input. The traditional approach for generating high frequency is by the frequency multiplication of low frequency generated by quartz or surface acoustic wave (SAW) oscillators. Resultant signal has the multiplied noise too. High frequency directly generated with high-quality factor microwave and mm-wave resonator oscillators suffer from their inherent limitations, such as bulky cavity and sensitivity to environment parameters.

The research in this field has been aided by optical means in last decade because the advancements in opto-electronics has indisputably changed the world. The past two decades also seen the developments in opto-electronic oscillator (OEO). This architecture can be used to produce spectrally pure sine waves in very high frequencies. The OEO was first demonstrated in the late 1990s and it is being developed continuously to have better parameters of performance. They employ high Q optical cavities[1] and opto-electronic feedback loops[2] to achieve this as well as employing coupled OEO architecture[3]. The first generations of OEO based on fiber delay lines suffered from major challenges of length of fiber in kilometer range, multimode behavior and frequency drift. Silicon photonics[4] helps to solve these problems.

In this paper, we propose an OEO architecture with micro ring resonator, Mach-Zehnder modulator and GaN-based radio-frequency (RF) amplifier to implement the 110 GHz OEO system. Two different models for the micro ring resonator (MRR) are considered, which are Okamoto and Klein model, to characterize the operation and a MATLAB model based on Klein model is utilized for simulation. MRR with silicon on insulator (SOI) technology is preferred as the fabrication SOI is compatible to the current complementary metal-oxide-semiconductor (CMOS) process.

The MRR amplifier is calculated to have 5.27 μm radius which gave a simulation with 16.79 dB as free spectral range (FSR). The RF amplifier design relies on a three-stage amplifier structure built on GaN based high-electron-mobility transistor (HEMT) as these transistors built on MMIC promises to be a good candidate

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in higher frequencies. This component is modelled with a hybrid-pi like model for GaN taking account of high frequency pinch-off model parameters. The integrated system with the proposed architecture is validated with Optisystem simulation with multiple iterations for 110 GHz operation.

An oscillator is a closed loop circuit as shown in Fig.1, which implements a positive feedback to satisfy certain conditions. The basic criteria for a sustained oscillation are whether it satisfies two conditions, called the Barkhausen conditions.

1. The loop gain of system must be greater than 1.
2. The phase shift of the feedback signal must be 2π after one turn in the loop.

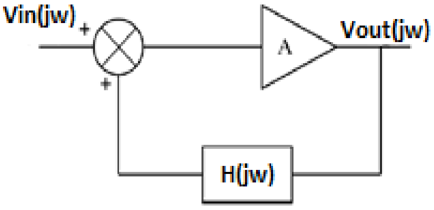


Fig.1 Block diagram of an oscillator

The output V_{out} is given as related to gain A and feedback transfer function as

$$V_{\text{out}}(\mathrm{j}\omega)=AV_{\text{in}}(\mathrm{j}\omega)+H(\mathrm{j}\omega)AV_{\text{out}}(\mathrm{j}\omega). \quad (1)$$

An initial noise of very small amplitude in the system is essential for starting up the oscillation in the system where this gets amplified and get stabilized as the signal circulates around the loop.

The MRR is the optical analog of acoustic whispering gallery modes (WGM). They are basically ring waveguides working as the resonant cavity for light with one or two other waveguides as input and output ports (as shown in Fig.2). Resonance happens in an MRR when the optical path length of the resonator is whole number multiple of the wavelength. Ring resonators therefore support multiple resonances. The parameter FSR defines the spacing between these resonances sand it is dependent on the length of the resonator. When the waves in the loop make a round trip having a phase shift that equals an integer times 2π, Constructive interference occurs within the channel and destructive interference occurs outside then channel leading to a comb-like spectral response. For an MRR with radius r and effective refractive index n_{eff}, the equation for the resonant wavelengths is given by

$$\lambda_{\text{r}}=\frac{2\pi rn_{\text{eff}}}{m}, \quad (2)$$

where m is an integer.

Silicon photonics is emerging as one of the most promising integration platforms for photonic devices in the last years. The availability of high refractive index contrast and sophisticated CMOS fabrication technology has enabled its use in MRR as we are able to produce silicon micro ring resonators (SMRR). With the use of silicon and its oxide (SiO_2), it is possible to make SMRRs with bend radius as low as 5 μm[5]. This also enables us to make extremely compact rings, even with an FSR over 20 nm at telecom wavelengths around 1 550 nm. The new fabrication techniques like the SOI processes makes the MRR in an ultra-compact package.

Monolithic microwave integrated circuit technology (MMIC) has progressed in such a way that we are able to fabricate compact chip RF amplifiers in the W-band of microwave frequency. This makes MMIC, the components of choice for the power amplification circuits of OEO designs. The current MMIC devices are fabricated on substrates, such as GaAs, InP, and GaN[6-8], as it can be used to fabricate topologies, such as HEMT. The fabrication techniques are also getting matured in the recent years such that we expect commercially available amplifiers releasing to the market soon for 110 GHz. We explored the possibilities of realizing RF amplifier with sufficient gain frequency response for the 110 GHz oscillator in this paper.

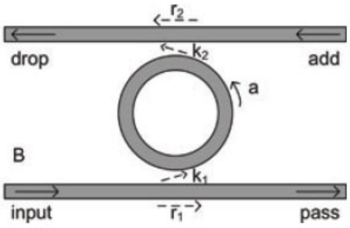


Fig.2 Add-drop micro ring resonator[5]

The modelling of these components and calculation of their characteristics for the 110 GHz oscillator system are carried out and further verified with simulations.

The architecture of the MRR based OEO and its frequency response corresponding to MRR output are depicted in the Fig.3. As we can see in the frequency graph, the laser input signal is added with a sideband after it gets passed through a Mach-Zehnder modulator. The micro ring resonator works as a frequency selective device, by selecting the frequency band 110 GHz away from this band. The high-quality factor and fairly large FSR of the MRR make this signal to be useful for spectrally pure output, if the MRR is designed properly. Each time the signal makes a roundtrip through the OEO loop, the 110 GHz signal gets more prominent.

One of the key design strategies is to select the FSR of the resonator accordingly so the output frequency around the laser frequency has to fall into one of the peaks as shown in the frequency domain diagram given in Fig.3. The FSR is chosen for this condition and also taken care that it belongs to the microwave domain.

Another advantage of using the micro ring resonator in the system is to eliminate the need of a high-performance bandpass filter as in the case of a conventional OEO design. We employ a Chebyshev type bandpass filter in the design, the only purpose of which is to reject the RF components outside the intended frequency band. Here the narrow band filtering that is used in the fiber delay line based OEO is not needed because the MRR does the function of frequency selection and mode hopping is avoided here.

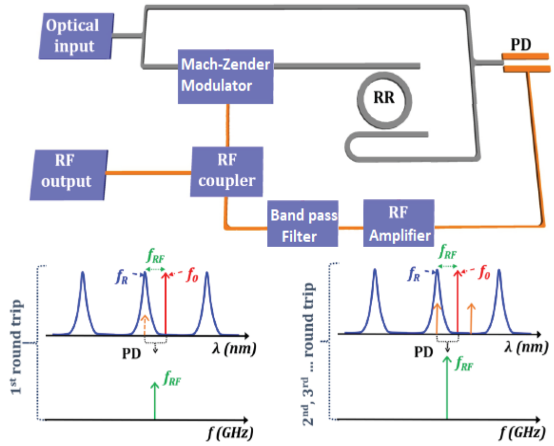


Fig.3 (a) The architecture of the MRR based OEO and (b,c) its frequency response corresponding to MRR output

Okamoto model: Katsunari Okamoto[9] investigates the transmission characteristics of independent planar optical waveguides and optical devices. The coupled mode equations are derived based on perturbation theory and practically important optical devices are considered to calculate coupling coefficients using concrete methods. For the MRR, input output relations are expressed as a first step. With this, the calculation of transmittance is done. Okamoto model introduces new parameters as

$$\begin{cases} x=(1-\gamma)^{1/2}\exp\left(\dfrac{\rho}{2}L\right) \\ y=\cos(\kappa\ell) \\ \phi=\beta L \end{cases}, \tag{3}$$

and the steady state transfer function of MRR[9,10] is given by

$$T(\phi)=\left|\frac{A}{A_0}\right|=(1-\gamma)\left[1-\frac{(1-x^2)(1-y^2)}{(1-xy)^2+4xy\sin^2(\phi/2)}\right]. \tag{4}$$

The assumption is that the input/output and resonator waveguides are having the same propagation constant.

Klein model: Klein E. J.[11] proposes to use MRR based components for fiber to home applications. Here, the micro ring resonator is considered as the basic building blocks of future opto-electronic circuit systems just like how a transistor used to be in the electronic counterpart. The paper combines the two models - directional coupler model and the ring waveguide model - into a combined model which makes the full characterization of the whole MRR structure. Fig.4 shows the signal flow diagram thus derived in terms of control engineering perspective.

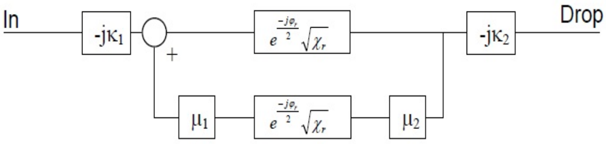


Fig.4 Signal flow diagram of the Klein model

The transfer function for output field at drop port is obtained by applying Mason's rule to this model:

$$\frac{E_{\text{Drop}}}{E_{\text{in}}}=\frac{a-K_1K_2\exp(\frac{-\mathrm{j}\phi r}{2})\sqrt{\chi_r}}{1-\mu_1\mu_2\exp(-\mathrm{j}\phi r)\chi_r}. \tag{5}$$

The transfer function for power is as given in the equation:

$$\frac{P_{\text{Drop}}}{P_{\text{in}}}=\frac{H}{1+F_{\text{c}}\sin^2(\phi/2)}. \tag{6}$$

The terms H and F_{c} here are intermediate variables for the equation, which are defined as

$$H=\frac{K_1^2K_2^2\chi_r}{(1-\mu_1\mu_2\chi_r)^2}, \tag{7}$$

$$F_{\text{c}}=\frac{4\mu_1\mu_2\chi_r}{(1-\mu_1\mu_2\chi_r)^2}. \tag{8}$$

With Okamoto and Klein models, the MRR is modelled into a quantitative mathematical model from a qualitative description, considering the effect of various parameters. If we closely examine them, these two models have inter-related parameters. Which model to use for a design is a choice to be made for ease of design. The parameters for the model are either related to coupling region between ring and port waveguides or the ring resonator itself. In this paper, Klein models is used for further analysis.

The design of the MRR is iterative so that we obtain the output very close to the target 110 GHz signal. The first step is to find out the Lambda1 frequency which is calculated here by adding the 110 GHz to the input laser frequency. The minimum FSR can be calculated here. Next step is to calculate the number of round trips according to the equation. The point to note here is that this figure has to be a whole number. The resultant number is calculated with multiples of FSR and to get a whole number for '*m*'. The other criteria being the result has to correspond to a manufacturable geometry too.

By iterative design, we assume 55 times minimum FSR and resonance at Lambda1, which is a reasonable approximation. The corresponding calculation provides us with the number of round trips '*m*' to be 31.917. This number being close to 32, the calculation is done for MRR radius as shown in Tab.1.

The result of the calculation is 5.271 9 μm radius for the MRR.

This is a practically possible value according the current SOI technology.

Tab.1 Calculation of MRR radius

Parameter	Value	Unit
n	1.5	
m	32	
L	33 124.579 4	nm
R	5.271 940	μm
FSR	48.577 6	nm
λ_0	1 552.714 6	nm
$\lambda_{0\ \mathrm{freq}}$	193 210	GHz
osc_{freq}	110	GHz

The MATLAB coding for Klein model is done so as to simulate the MRR output in the Optisystem. Transfer function for the Klein model is sampled in the frequency domain for this co-simulation. The radius of the MRR is made a user-controlled parameter, which can be entered, through the Optisystem user interface. This makes it easier for trials with different geometry of MRR.

Selection and design of RF amplifier for this project focuses on the MMIC technology. GaN based design attracts the attention due to its very good figure of merit. The advantages include low on-state resistance, small parasitic capacitances and high critical electric field.

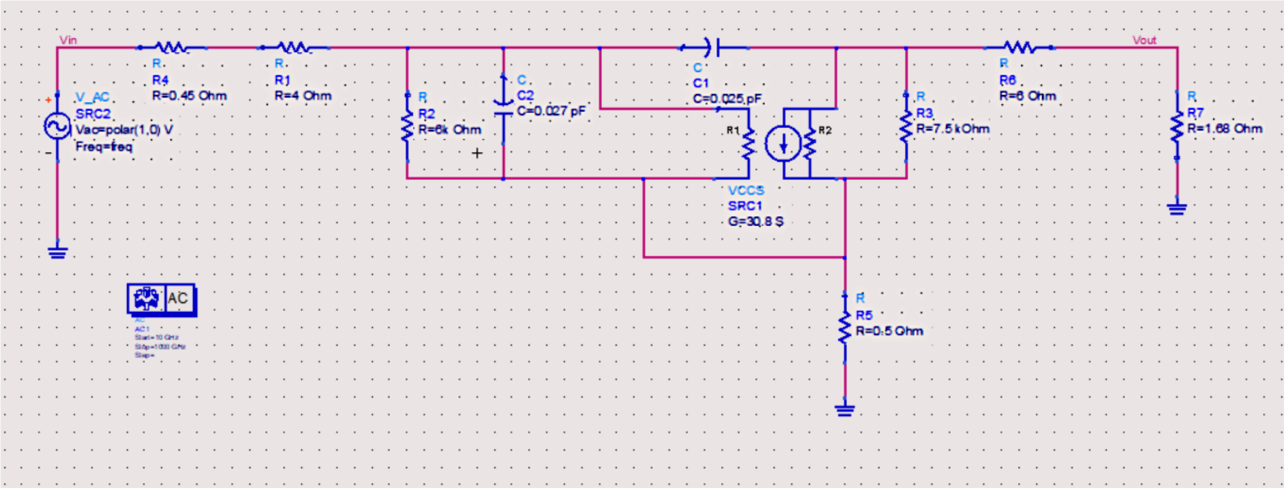


Fig.5 Single stage GaN amplifier simulation

We modelled the GaN based power amplifier architecture[12] using high frequency modelling and simulated the structure with the help of Agilent ADS software.

The paper by Hou Yanfei et al[6], describes the 2×40 μm architecture developed based on GaN HEMT devices for 110 GHz frequency. The paper presents a RF amplifier as a single ended three-stage amplifier where the third stage is a parallel cascade class-AB amplifier so that the linearity and efficiency are improved. The measurement is extrapolated above 50 GHz to find out gain. Our project models the GaN based power amplifier architecture using these high frequency parameters. Luo Xiaobin et al[13] describes the equivalent model of GaN based HEMTs for millimeter-wave applications. They have developed this model based on open-short test structure and reverse cut off method.

High frequency model: An Improved model under pinch-off bias condition, suitable for high frequency applications, is proposed by G Janjum et al[14]. This model overcomes the difficulties of high frequency simulation as it considers the reverse bias Schottky resistance effect.

Parameters for class-AB amplifier: The improved modelling is proposed[15] for the GaN HEMT on the Si substrate, which also takes into account the parasitic buffer loading effect. This model also accounts for self-heating and trapping effects that occurs during high power operating conditions.

The models we considered in the previous section are strikingly analogous to the BJT characterization using hybrid-pi modelling, the frequency dependent current gain or h_{fe} can be derived using short circuit analysis of the common emitter configuration.

$$h_{\mathrm{fe}}=\frac{I_c}{I_b}=\frac{g_m-sC_\mu}{\dfrac{1}{r_\pi}+sC_\pi+sC_\mu}. \tag{9}$$

It is evident from the equation that the frequency drops at higher frequency.

The model of RF amplifier with GAN HEMT transistor is drawn in Agilent ADS software in order to simulate the circuit frequency response and to find out the signal again at frequency of 110 GHz. The selected values of intrinsic and extrinsic elements are as shown in Fig.5. The component values of the equivalent model are taken as described in the analysis - improved pinch-off model and optimized parameters for power amplifier application[14-16] are taken for reference.

A closed loop system is constructed in Optisystem software for OEO which has the provision for positive feedback[12]. The "initializer block" from Optisystem tools library is used for start-up of the system with initial noise input. MATLAB components are used for Mach-Zehnder modulator and micro ring resonator. RF amplifier used has the gain according to the simulation results of GaN based amplifier.

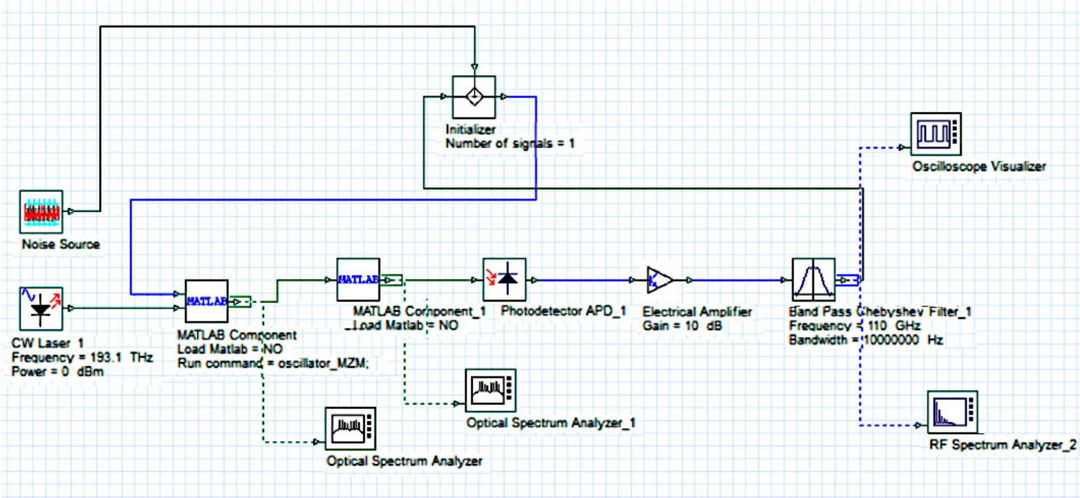


Fig.6 The 110 GHz OEO loop implementation in Optisystem

MRR calculation: The values for coupling coefficients, group index and loss factor are taken as given in the paper from Edwin Jane Klein[11]. The geometry of the MRR is obtained from the calculation as described above considering 5.27 μm radius for the structure. The calculation is made with corresponding equations of Klein model as shown in Tab.2. Graph is plotted in excel sheet with the results on 185 nm to 202 nm wavelength. The result clearly shows a frequency selective behavior of the MRR. The plot in Fig.7 verifies the narrow band filter like response of MRR having a comb like repeating optical resonant frequencies. The calculated values show very effective characteristics of the designed MRR for the design of OEO system.

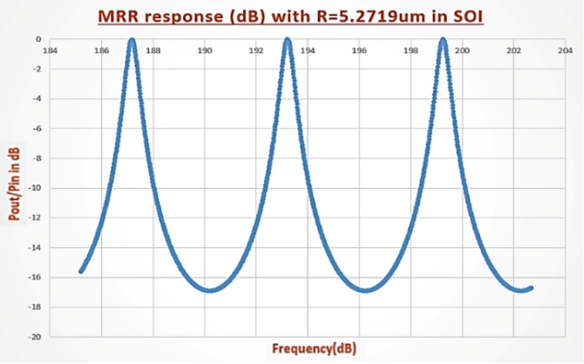
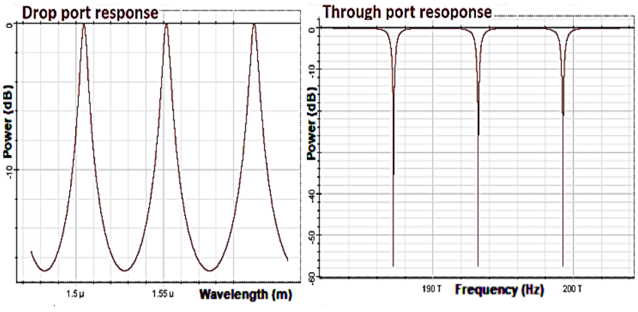


Fig.7 Plot of calculated MRR response with *R*=5.271 9 μm in SOI

MRR simulation results: The equation is implemented as with the Klein model for the power transfer function. Optical spectrum analyzer is placed at the output of the MRR block for obtaining the results in frequency domain as in Fig.8. The results are plotted in dB scale.

The peak of the waveform is observed at 193.21 THz and distance to the resonance peak is found to be more than 6 THz. The through port shows an opposite behavior to drop port as the response is having frequency elimination at resonant frequencies confirming the expected behavior.



(a) (b)

Fig.8 MRR simulation results of (a) drop port and (b) through port

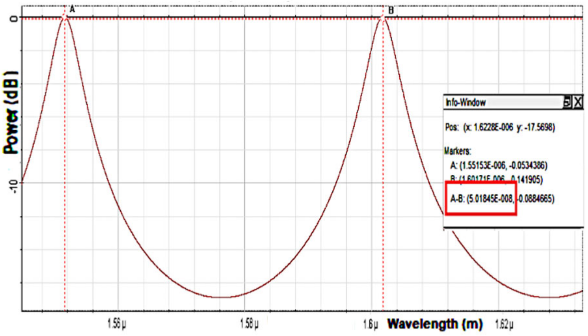
The important parameters obtained with calculation and simulation are summarized in Tab.2.

Tab.2 Comparison of MRR calculation and simulation

Performance parameter	Theoretical calculation	Simulation result
Drop port insertion loss	0.010 9 dB	0.011 6 dB
Filter rejection ratio	16.79 dB	16.9 dB
Filter bandwidth	4.36 nm	4.366 nm
Through port insertion loss	0.091 8 dB	0.089 8 dB
FSR of MRR	48.52 nm	50.18 nm

The measurement of simulated results is plotted as in Figs.9—11.

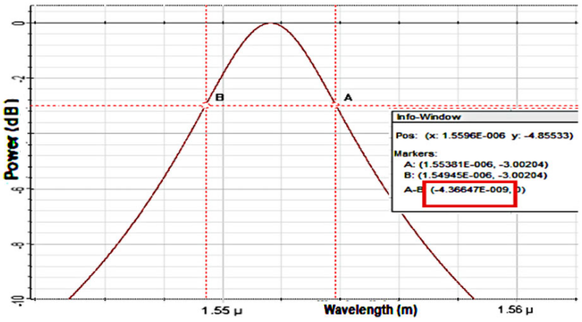
It is evident from the table that both the calculation and simulation results show excellent agreement with each other. The results from these analyses show very close as well as reasonable values. For example, the FSR is calculated to be 48.52 nm whereas the simulation shows a measurement of 50.18 nm plotted as in Fig.9.



Pos: (x: 1.6228E-006 y: -17.5698)
Markers:
A: (1.55153E-006, -0.0534386)
B: (1.60171E-006, -0.141905)
A-B: (5.01845E-008, -0.0884665)

Fig.9 FSR measurements of MRR from simulation

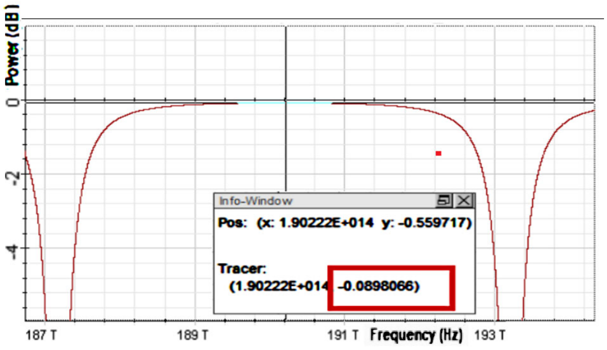
The bandwidth calculated is 4.361 nm which corresponds to a quality factor of 0.356×10^6. The -ty factor is a high value that indicates stability over resonance shifts. The bandwidth obtained from simulation is a close value as shown in Fig.10.



Pos: (x: 1.5596E-006 y: -4.85533)
Markers:
A: (1.55381E-006, -3.00204)
B: (1.54945E-006, -3.00204)
A-B (-4.36647E-009, 0)

Fig.10 Measurements of bandwidth of MRR from simulation

The through port insertion loss in the design is derived as a very low value as shown in Fig.11 to be 0.089 dB. The observation from simulation results gives confidence to proceed with this model for OEO integration.



Pos: (x: 1.90222E+014 y: -0.559717)
Tracer:
(1.90222E+014 -0.0898066)

Fig.11 Measurement of through port insertion loss of MRR

Single stage amplifier simulation results: The simulation made is in the Agilent ADS software with the AC simulation controller block placed inside the design. Linear frequency sweep is done in the range of 10 GHz to 1 THz frequency. The signal gain is noted as $V_{\text{out}}/V_{\text{in}}$.

The frequency response of signal gain is shown in Fig.12. We observe that the output signal gain starts dipping after 50 GHz with higher slope. The result of the simulation is that at 110 GHz frequency we obtain a gain of 5 dB.

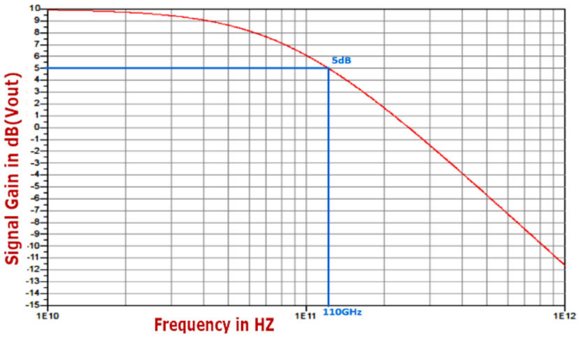


Fig.12 Signal gain versus frequency for single stage GaN amplifier

Three-stage amplifier simulation results: It is seen from the graph that theḨ gain starts dipping from a much lesser frequency range. The result of the simulation is as shown in Fig.13.

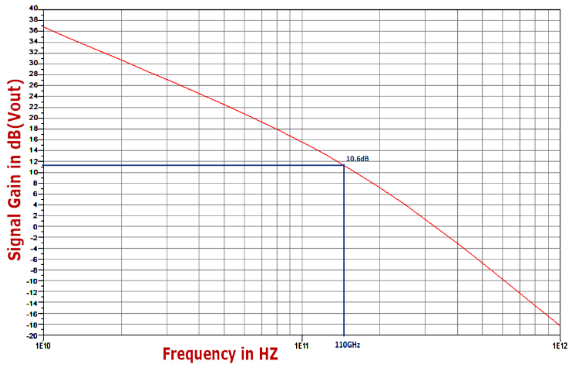


Fig.13 Signal gain versus frequency for three-stage GaN amplifier

The gain obtained at 110 GHz is 10.6 dB. This value is in accordance with Ref.[6] as it is extrapolated as greater than 10 dB for the amplifier. Therefore, OEO simulation is done with integrating RF amplifier with 10 dB gain.

The OEO system with all the components is simulated in the Optisystem software with two iterations. The initializer block is utilized for injecting initial noise. Appropriate measuring instruments are placed at the output and intermediate points in order to observe the signal at these points. The time domain and frequency domain waveforms are observed at the OEO output as shown in Fig.14.

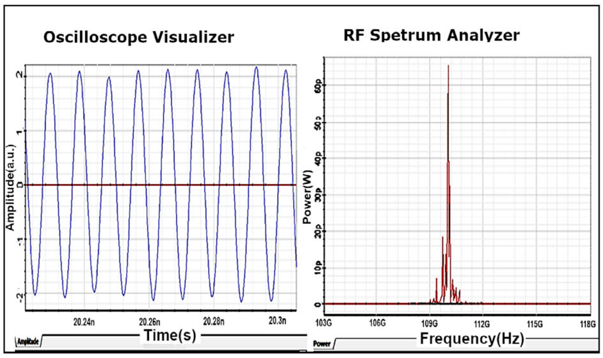


Fig.14 OEO output in (a) time and (b) frequency domains

The results clearly show a very sinusoidal signal with the visual observation in time domain. Measured frequency is 110 GHz as the time period is close to 9.09 ps. A spectrum analyser placed at the RF output of the loop shows a sharp peak right around the frequency of 110 GHz indicating a clean sinusoidal signal at this frequency.

The design and simulation have been done for the MRR and RF amplifier towards the development of OEO generating an ultra-pure sinusoidal signal at 110 GHz. Okamoto and Klein models of MRR compared and found to be having inter-related parameters. Simulations and calculations of MRR with Klein model showed performance parameters to be matching. The MRR designed on SOI characteristics are suitable for 110 GHz oscillator applications where the dimensions are chosen accordingly with 5.27 μm radius and the design is simulated. For the RF-amplifier, the improved model taking account of pinch-off bias condition is suitable for higher frequency applications. A signal gain of more than 10 dB is confirmed using simulations for GaN HEMT at frequency of 110 GHz. The proposed architecture of the integrated system is validated with Optisystem simulation. The dimensions of a micro ring resonator for a 110 GHz oscillator are derived and found to be within current manufacturable limits. The suitable modelling strategies are also derived for demonstrating the simulation for such an oscillator with micro ring resonator and RF amplifier modelling. Our work put forward a OEO design achieving miniaturization which also translates to higher energy efficiencies. The micro ring resonator based OEO is superior compared to traditional fiber-based designs because we can eliminate bulky equipment as well as frequency hopping.

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