Improving underwater imaging in an amplitude modulated laser system with radio frequency control technique

1 INTRODUCTION

The development of laser scanners for three-dimensional (3D) imaging of targets in submarine environment is a research area of interest for several potential users. These include, for instance, offshore oil companies for pipelines and platforms inspection, military institutions for target recognition and governmental organizations for survey of the submarine archaeological heritage. The interest stems from the potentiality of laser devices of visualizing farther than conventional cameras [1]. Up to a decade ago, laser imagers based on amplitude-modulated (AM) lasers at radio frequency (RF) had been receiving less attention than systems operating with pulsed or non-modulated CW laser sources [2], despite the fact that 3D target imaging in an AM device relies on the measurement of the signal phase and does not require an a priori estimation of target distance, or even a dual laser illumination. Nevertheless, the recent advent on the market of diode lasers emitting radiation at $\lambda = 405$ nm and propagating in a 25 m-long test tank filled with water of varying turbidity. In addition, the interest towards AM systems, mainly in view of the possibility of optical noise rejection based on RF filtering characterizes AM systems. The first experimental demonstration of the existence of a cut-off frequency in the RF range due to the low-pass filter frequency response of the ocean water backscattering for a 100 ps laser pulse excitation dates back to 2000 [4], following a theoretical analysis of L. Mullen et al. [5]. Improvements in underwater target contrast were soon after demonstrated by modulating the pulse’s intensity above the cut-off value [6]. However, an experimental demonstration of the low-pass frequency response of water backscattering for continuous AM laser excitation is still lacking [7]. Beside the relevance for validating theoretical models inspired by previous studies and overhauled to better simulate our device performances [8, 9], these experimental data could give insights on how instrumental, rather than physical parameters, shape the filter function.

In the present paper we report the results of an experiment aimed at measuring the frequency response of water backscattering as recorded by an AM device based on a diode laser emitting radiation at $\lambda = 405$ nm and propagating in a 25 m-long test tank filled with water of varying turbidity. In addition, we also demonstrate that better performances are obtained when the device is operating in the stop-band fre-
frequency region, by recording the linear profile of a simple target immersed at 3.7 m from the entrance window of the tank.

The paper is organized as follows: in Section 2 a simple theoretical approach is used to illustrate the physics underlying the low-pass filter behavior of water backscattering under AM excitation, in Section 3 the experimental apparatus is described and in Section 4 the results of experimental measurements reported.

2 BASIC THEORY

In an AM laser 3D imager the intensity of a spatially collimated laser beam is sinusoidally modulated at RF. The range of the target region illuminated by the laser is determined by measuring the phase shift, with respect to a reference signal, of the reflected radiation. A 3D image can be recorded by sweeping the laser onto the target’s whole surface. The reflected radiation is collected by a lens of radius \( r_0 \), mounted in a bistatic geometry where \( r_{rec} \) is the laser-receiver separation. The whole receiving optics is characterized by an angular field of view (FOV) \( \theta_{FOV} \). If the target is immersed in water, a considerable degradation on the image quality comes from a modulation frequency region, by recording the linear profile of a simple target immersed at 3.7 m from the entrance window of the tank.

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signal provided by a lock-in amplifier (Standford Research SR844), which also measures the intensity and the phase difference, with respect to a reference, of the water backscattered radiation. The latter is collected by a short-focal-length lens of radius \( r_0 = 2.5 \text{ cm} \), focused and conveyed onto a fast photomultiplier detector (Hamamatsu H5783), forming a receiving optical stage with an angular field of view of \( \theta_{\text{FOV}} = 0.117 \text{ rad} \) (semiangle). A bistatic optical layout with a spatial separation of \( r_{\text{rec}} = 0.2 \text{ m} \) between the light source and the receiver was adopted. The AM laser beam could freely propagate inside a black-walled 25 m-long test tank, equipped with an anti-reflection coated entrance optical window. Signal contribution originating from unwanted reflections at the bottom wall of the tank was suppressed by means of a beam dump. During the experiments, the water extinction coefficient was varied by adding calibrated quantities of skim milk and measured using a PerkinElmer Lambda 25 UV/vis spectrometer in order to estimate the water turbidity.

4 EXPERIMENTAL RESULTS

In order to experimentally prove the low-pass filter dependence of the water backscattered power when the excitation comes from an AM laser source, measurements were performed with the test tank initially filled with tap-water \((k = 0.5 \text{ m}^{-1})\). The extinction coefficient was subsequently increased up to 2.1 \text{ m}^{-1} by adding controlled quantities of skimmed milk. From an experimental point of view, a major concern arises from the dependence of \( m \) on \( f_m \), that was then measured, as shown in Figure 3.

Up to the investigated frequency the modulation index shows an oscillating behavior, already observed in other AM systems [12] and likely due to a frequency dependent laser impedance, with a maximum value of 0.88 at 0.5 MHz and minimum of 0.71 around 80 MHz. For frequencies larger than 140 MHz, \( m \) falls rapidly to values lower than 0.5 making the system not reliable for quantitative measurements.

The results of three experiments at different values of \( k \) are reported in Figure 4, where the experimental data are normalized to \( m \). The experimental findings confirm the expected low-pass filter dependence and enable to verify that the width of the pass-band region is an increasing function of \( k \). Nevertheless, it must be highlighted that the Butterworth’s low-pass filter dependence, deriving from the simplified model described in Section 2, does not properly fit the experimental data, as the simulation for \( k = 0.5 \text{ m}^{-1} \) reported in Figure 4 shows. Similar deviations can be also found for the other two experimental curves. This occurs because our experimental test bed significantly deviates from the ideal system assumed to find out Eq. (2), where heavy assumptions were made to simplify the treatment.

Adopting the more appropriate radiative transfer formalism to account for the bistatic layout and the finite value of the FOV introduces a new whole level of complexity into the theoretical treatment. Nevertheless, the here reported experimental data support our more accurate theoretical findings [9], resulting in an analytic expression in integral form for the re-
received backscattered power, where both water optical parameters and system factors, like $r_{\text{rec}}$, $\theta_{\text{fov}}$, and $r_0$, compete to shape the low-pass filter function. However, the experimental conditions did not enable a direct determination of all the parameters entering the theoretical model in [9], thus not allowing at this stage a numerical simulation of the data in Figure 4, though a fitting procedure reproduces them quite well and with reasonable values for the unknown parameters.

After experimentally demonstrating the efficiency of optical noise suppression by means of modulation frequency control, the next experimental step was to verify an enhancement in target visualization when the device operates in the regime $f_m \gg f_c$. For this purpose we used as target a dark-gray-painted, sanded, mostly diffusive, metallic calibrated ladder with 1 cm high steps, apart from the first step whose height was 4 cm. The ladder was immersed at 3.7 m from the optical window of the test tank and its 8 cm long horizontal profile scanned in 80 pixels. The water attenuation coefficient was 0.5 m$^{-1}$ resulting in a $f_c = 17.9$ MHz. The results of two different scans at $f_c > f_m = 10$ MHz and $f_c < f_m = 85$ MHz are reported in Figure 5.

Despite for $f_m = 85$ MHz the laser is operating with $m \sim 0.72$, the corresponding line profile reproduces with more accuracy the target shape than that recorded at $f_m = 10$ MHz when $m \sim 0.87$. Since both the target signal $S$ and the optical noise $N$ scale linearly with $m$, the improvement in the image quality resulting in a better target profile reconstruction is rooted in the enhancement of the signal-to-noise ratio $S/N$ due to the experimentally demonstrated low-pass filter dependence of $N$ on $f_m$. In both the recorded profiles, the smoothness of step-to-step jumps is a consequence of poor laser focalization (beam spot diameter on the target 0.5 cm).

It must be noted that a complete extinction of the optical noise can be obtained only for $f_m/f_c \gg 10$ as Figure 1 shows, a condition out of the operating range of our equipment. This means that a residual optical noise contribution is still present at $f_m = 85$ MHz, as suggested by a quantitative analysis of the scanned linear profile. In fact, for the target signal, the measured phase $\phi$ depends linearly on target range $D$ through the relation $\phi = 4\pi mn_D/c$. By assuming $n = 1.344$, experimental data give $(\Delta\phi)_{\exp} = 2.3^\circ$ for the 1 cm steps, a value lower than the theoretical prediction $(\Delta\phi)_{\text{tho}} = 2.73^\circ$. The observed reduction of the measured range with respect to the real one is a property expected in our device when the optical noise contributes non negligible to the detected signal. In fact the measured phase of a target at distance $D$ is given by $\phi_{\exp} = \tan^{-1}(I_Q + I_P^0)/(I_Q^0 + I_P^0)$ where $I_Q$ and $I_P$ are the quadrature and in-phase components of the signal contribution from target ($t$) and from noise ($r$) respectively [13]. By using for the noise contribution the results obtained in Eq. (2) and for the target $I_Q^n = I \cos (4\pi mf_m D/c)$ and $I_P^n = I \sin (4\pi mf_m D/c)$ it is possible to demonstrate that $(\Delta\phi)_{\exp} < (\Delta\phi)_{\text{tho}}$ for $I_Q^n, I_P^n \neq 0$.

5 SUMMARY

The availability of a 25 m-long test tank allowed us to experimentally investigate the low-pass-filter frequency dependence of the optical noise detected in an AM laser system aimed at 3D imaging of immersed target. The deviation from the Butterworth filter shape was expected on the basis of ongoing theoretical studies. In addition, improvements in the target profile reconstruction were demonstrated for the device operating in the stop-band frequency region. As far as we know, this is the first experimental demonstration that the phase measurement accuracy of an AM laser 3D imager can be enhanced just by adopting a modulation technique above the cut-off frequency for the rejection of optical noise. Advances in the theoretical studies, together with improvements in our experimental set-up, are in progress for providing a theoretical and experimental reliable estimation of the $f_c(k, r_0, \theta_{\text{fov}})$ function. At the same time, these investigations are also expected to shed light on the role played by the in-phase and quadrature components of the optical noise, just sketched here, and to ascertain the advantages of a 3D imaging system based on demodulated detection.

FIG. 4 Normalized backscattered power vs. laser modulation frequency measured for different water attenuation coefficients: (●) $k = 0.5$ m$^{-1}$, (○) $k = 1.1$ m$^{-1}$, (■) $k = 2.1$ m$^{-1}$. The continuous curve is the plot of Butterworth’s filter function in Eq. (2) for $k = 0.5$ m$^{-1}$.

FIG. 5 Linear scan of the target profile for (a) $f_m = 10$ MHz and (b) $f_m = 85$ MHz.
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References


